Higgs via Vector Boson Fusion

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http://theory.fnal.gov/jetp

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ATLAS Experiment

Outline

Introduction

- Higgs, Higgs via vector boson fusion (VBF)
- ATLAS at LHC

Focus on similar final states

- VBF $H \rightarrow WW^* \rightarrow e\,\mu\; \nu_e\,\nu_\mu$
- VBF $H \rightarrow \tau\tau \rightarrow \ell\, h\; \nu_\ell\,\nu_\tau\,\nu_\tau$

Missing E_T (MET)

2 lepton-like objects

Putting it together

References

[a] HWW, ATLAS-CONF-2013-030 - Mar. 2013

[b] Combo, Phys. Lett. B726 (2013) 88 - Oct. 2013

[c] $H\tau\tau$, ATLAS-CONF-2013-108 - Dec. 2013

Higgs found at 125 GeV

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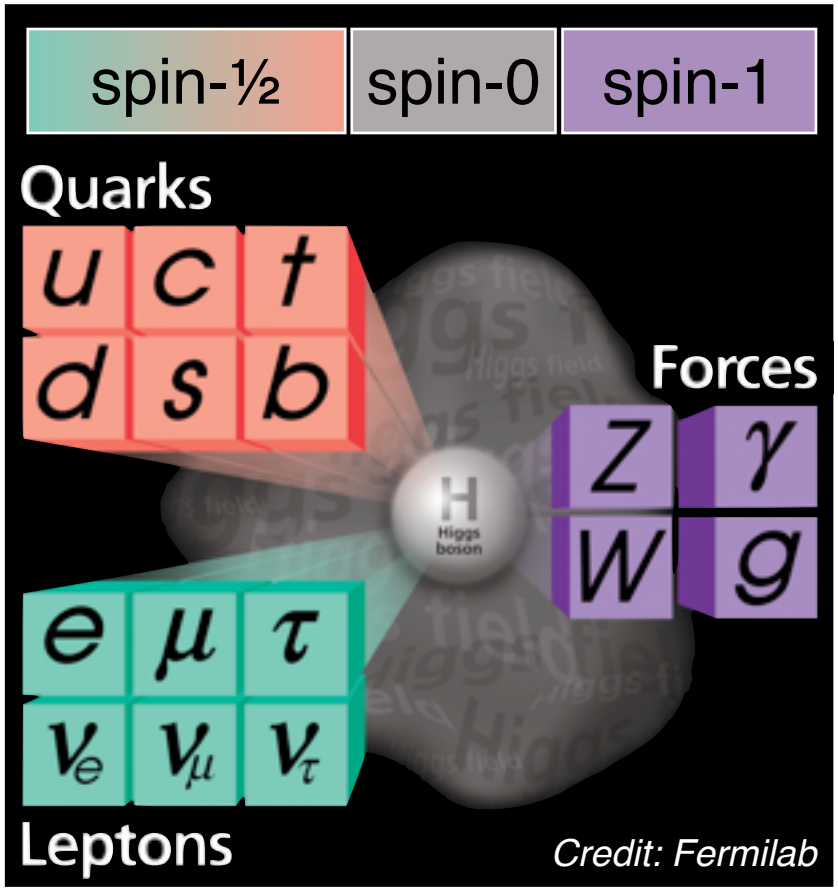
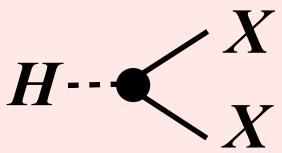
Allows fermion mass terms, restores electroweak symmetry



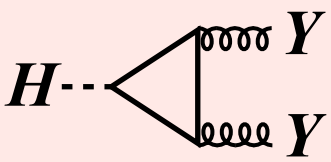
Divide into two groups

Tree relation for massive "X"



g_X

Loop relation for massless "Y"



g_Y - effective

Higgs boson theory - all true?

Higgs boson theory

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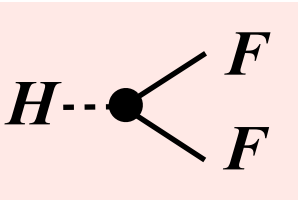
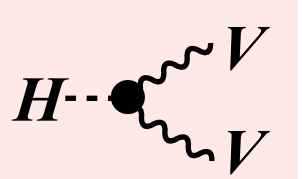
Massive M

Fermions $F \equiv q, \ell$



$$g_F \propto -\frac{M_F}{vev}$$

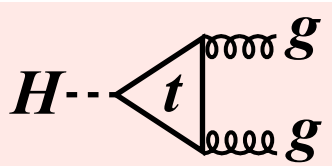
Vector bosons $V \equiv W, Z$



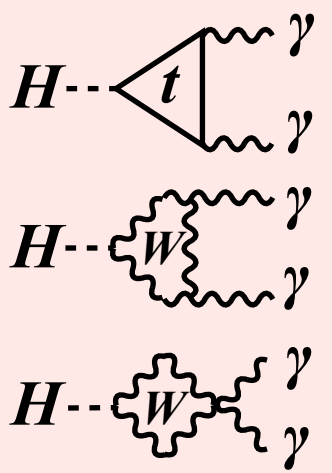
$$g_V \propto +2\frac{(M_V)^2}{vev}$$

Massless

Gluon g

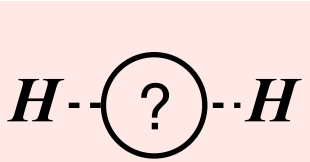


Photon γ

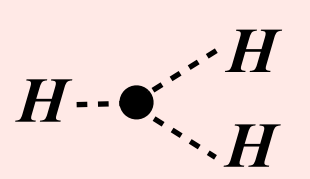


Beyond scope of talk

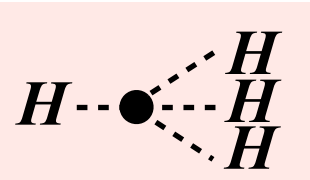
Higgs mass stabilization



Higgs self-interaction



$$g_{2H} \propto -3\frac{(M_H)^2}{vev}$$



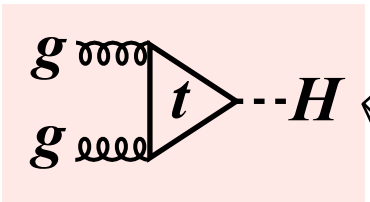
$$g_{3H} \propto -3\frac{(M_H)^2}{vev^2}$$

Lots to probe experimentally at the LHC.

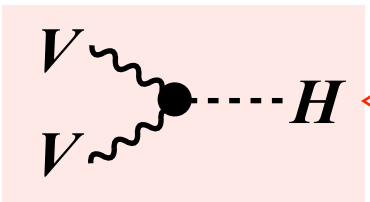
What's measured

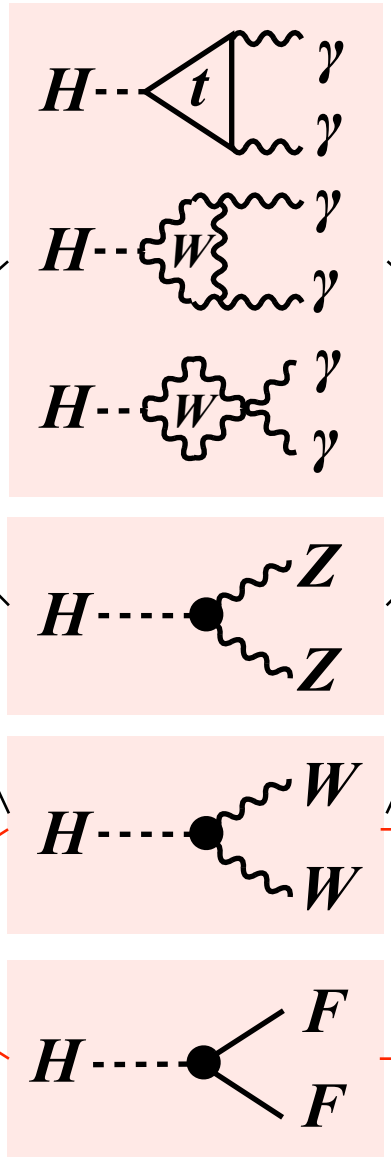
Higgs productions Higgs decays

Gluon-Gluon Fusion (ggF), dominant at LHC



Vector Boson Fusion (VBF), sub-dominant





Discovered Higgs with ggF production with

ggF → H → bosons

Now have evidence of VBF production with

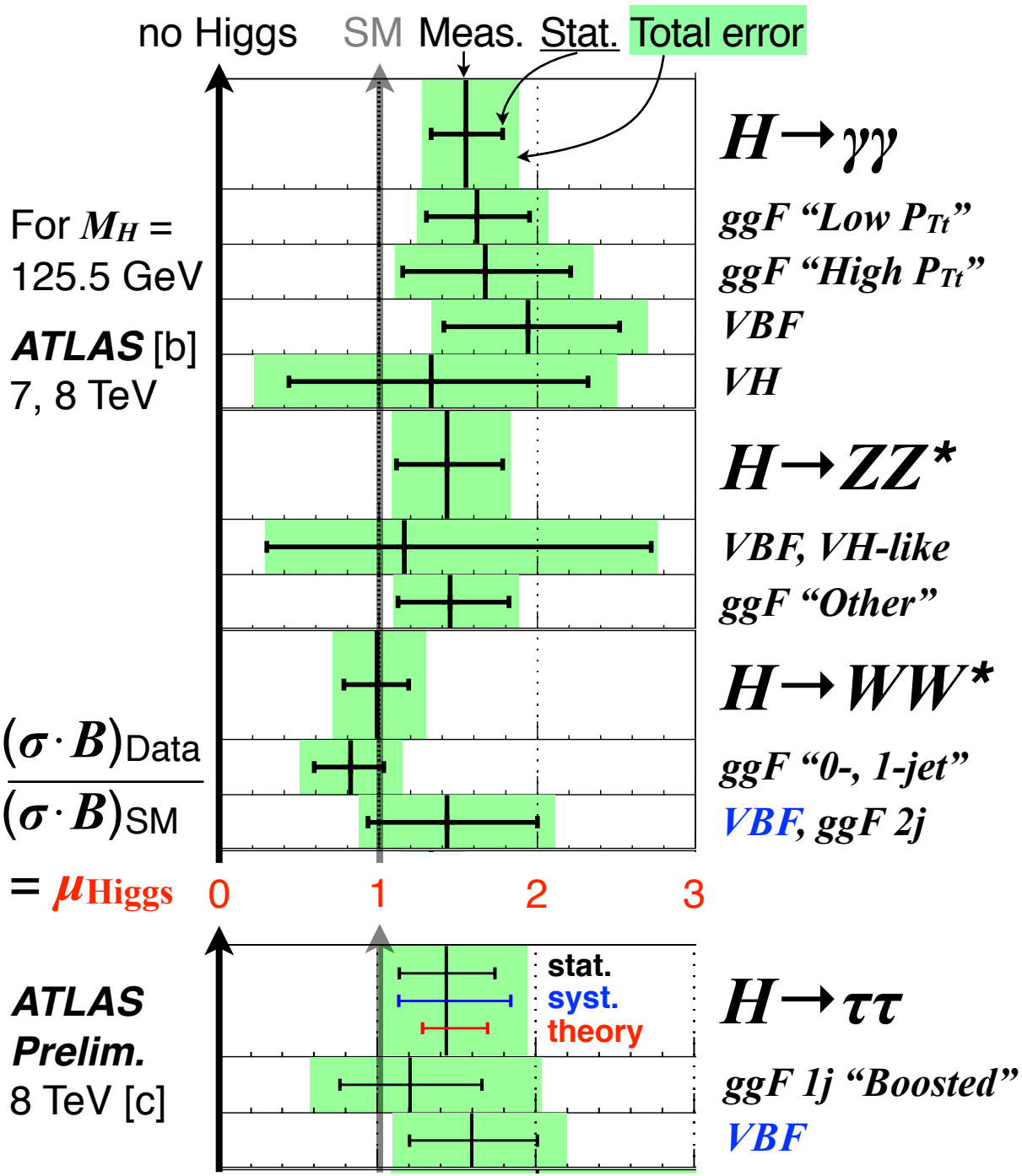
VBF → H → bosons

Only depends on g_V

Best direct constraint on g_F

ATLAS Higgs summary

Hong



I describe two analyses

Why VBF HWW

- I worked on it
- Best g_V, VBF HWW 2.5σ

Why VBF $H\tau\tau$

- Penn student work
- Direct g_F, $H\tau\tau$ 4.1σ (Dec.)

Important now, also Run-2

	ggF,	VBF
WW^*	yes	better S/B
$\tau\tau$	good	best

Analysis similarities

VBF $H \to WW^* \to e\mu$, VBF $H \to \tau\tau \to \ell h$

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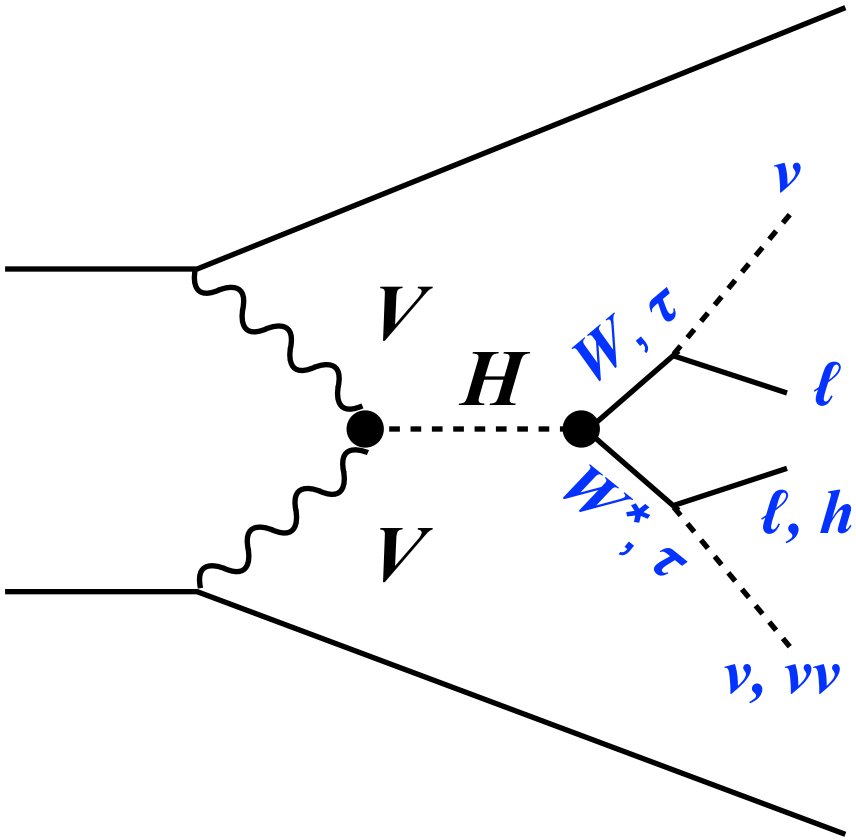


Two jets, two "leptons," *MET*

Analysis similarities

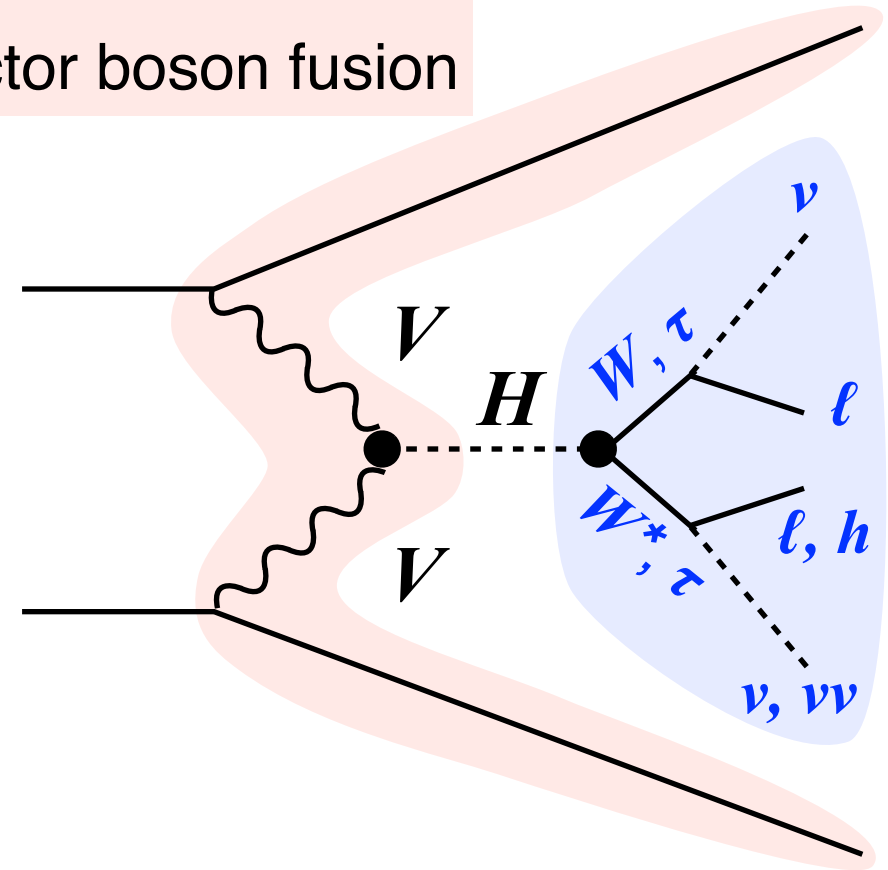
VBF $H \to WW^* \to e\mu$, VBF $H \to \tau\tau \to \ell h$

Hong

Tag production

Same

- Vector boson fusion



Tag decay

Similarities

- Trigger on e, μ
- 2 "leptons," 2 neutrinos
- MET, no sharp mass peak

Differences

- Decay kinematics physics
- One $\tau \to hadronic$

Two jets, two "leptons," MET

LHC as a vector boson collider

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Vector-boson fusion

Cahn, Dawson, PLB 136 (1984) 196

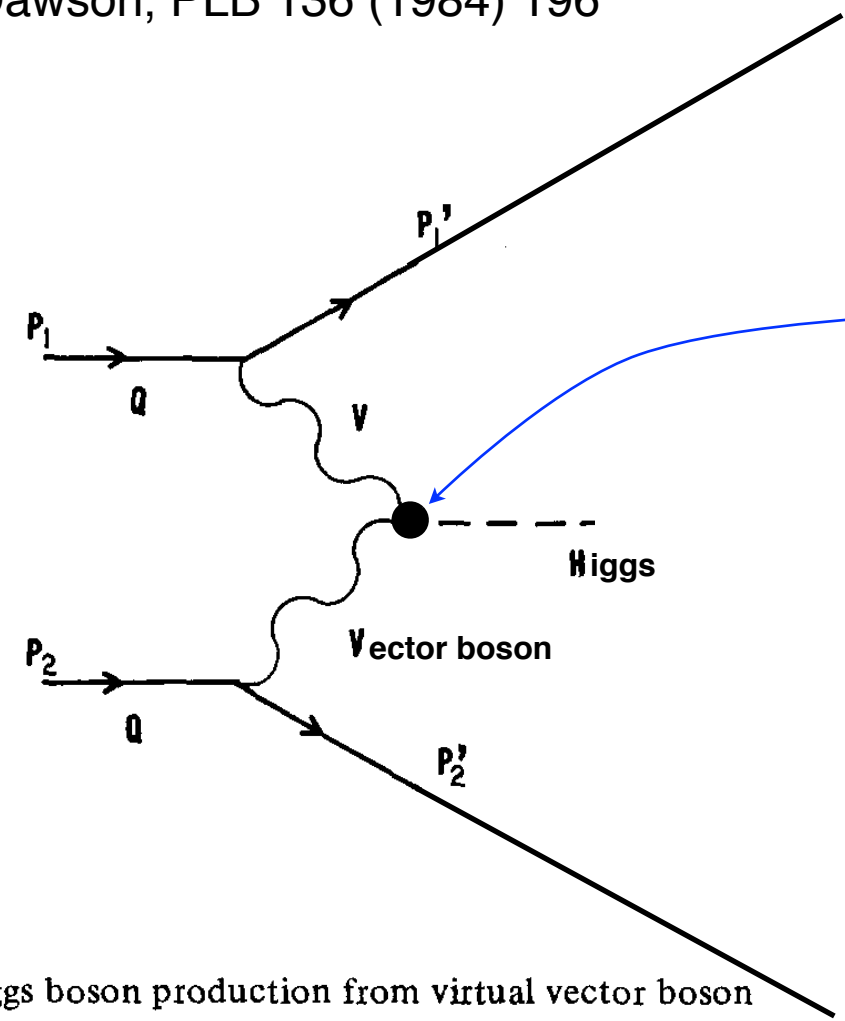

Fig. 1. Higgs boson production from virtual vector boson pairs (V = W or Z). The initial state quark (or anti-quark) momenta are p_1 and p_2 and the corresponding final state momenta are p_1' and p_2'. The momenta of the virtual vector bosons are q_1 and q_2.

VBF jet: high-P_T, high-η

How rates relate to g_V

- WW^* rate $\propto |g_V{}^2|^2$
- $\tau\tau$ rate $\propto |g_V \cdot g_F|^2$

All VBF Higgs inputs to g_V

Major backgrounds

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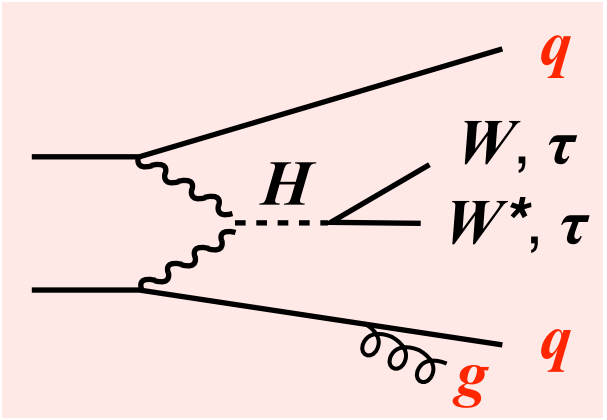
Energy deposits Jets

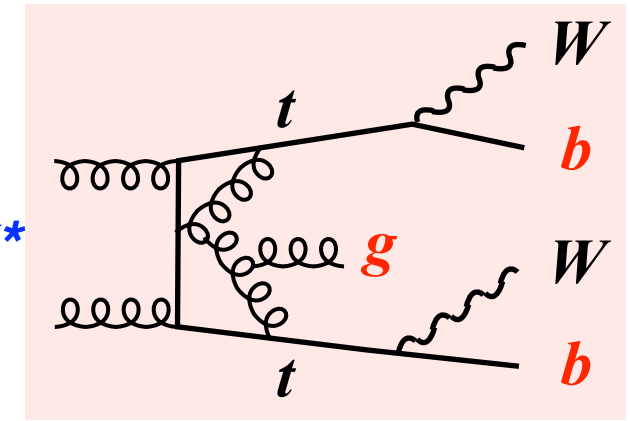
VBF Higgs



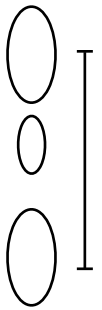
No color near *H*
No extra jets inside

Jets widely separated

ttbar, bkg. to *WW**

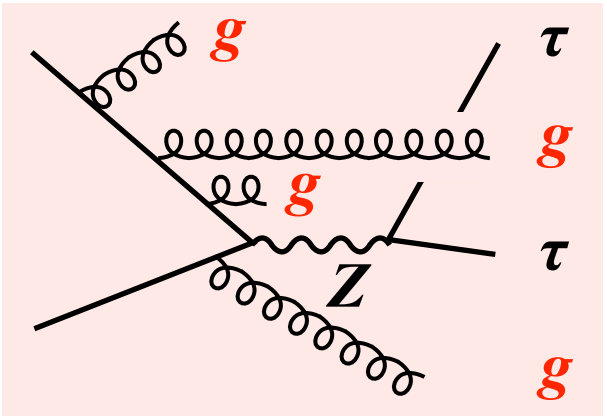


Hadronic activity

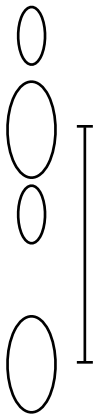


Jets not as separated

Z jets, bkg. to *ττ*



Hadronic activity



Jets not as separated

General feature of VBF production

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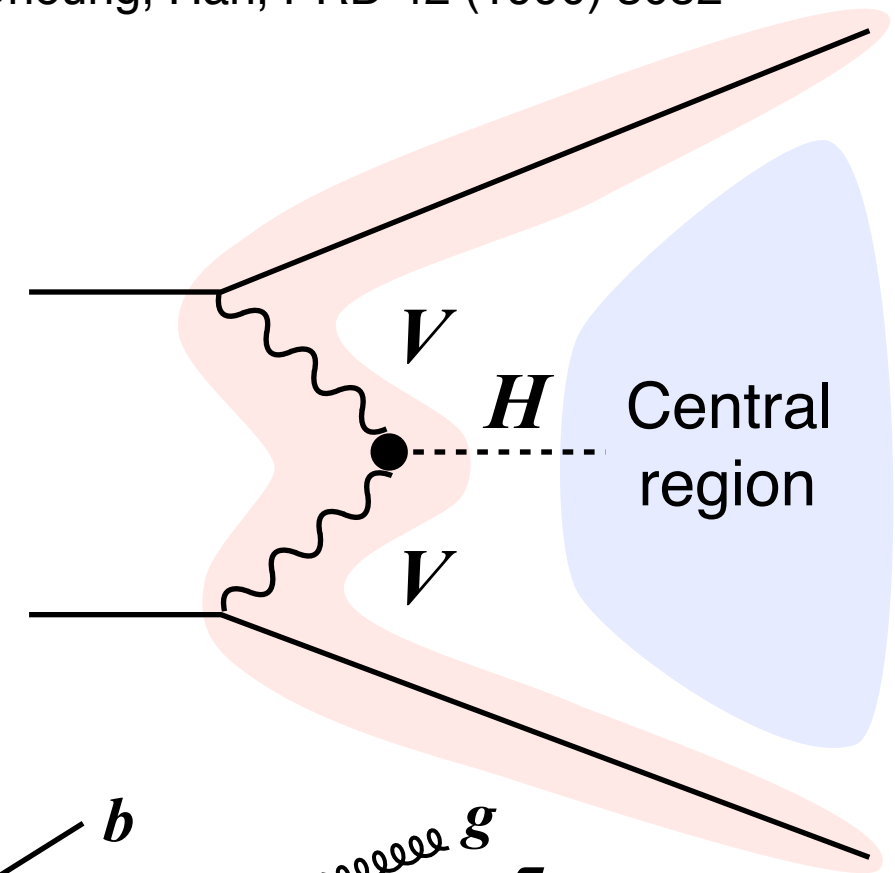
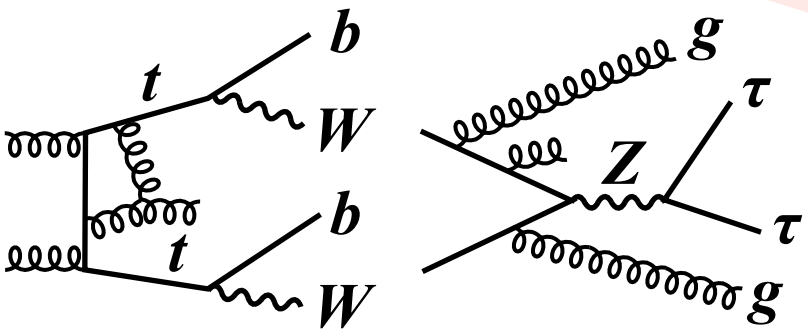
VBF “central region”

Zeppenfeld, Rainwater, PRD 60 (1999) 113004

Barger, Cheung, Han, PRD 42 (1990) 3052





Why

- Vector bosons are colorless
- No color between jets

Consequence 1

- Less hadronic activity between jets in VBF

Consequence 2

- Higgs decay daughters between jets in VBF

Effective in rejecting non-VBF

VBF jets

Hong

Two highest-P_T jets separated by $\Delta\eta$

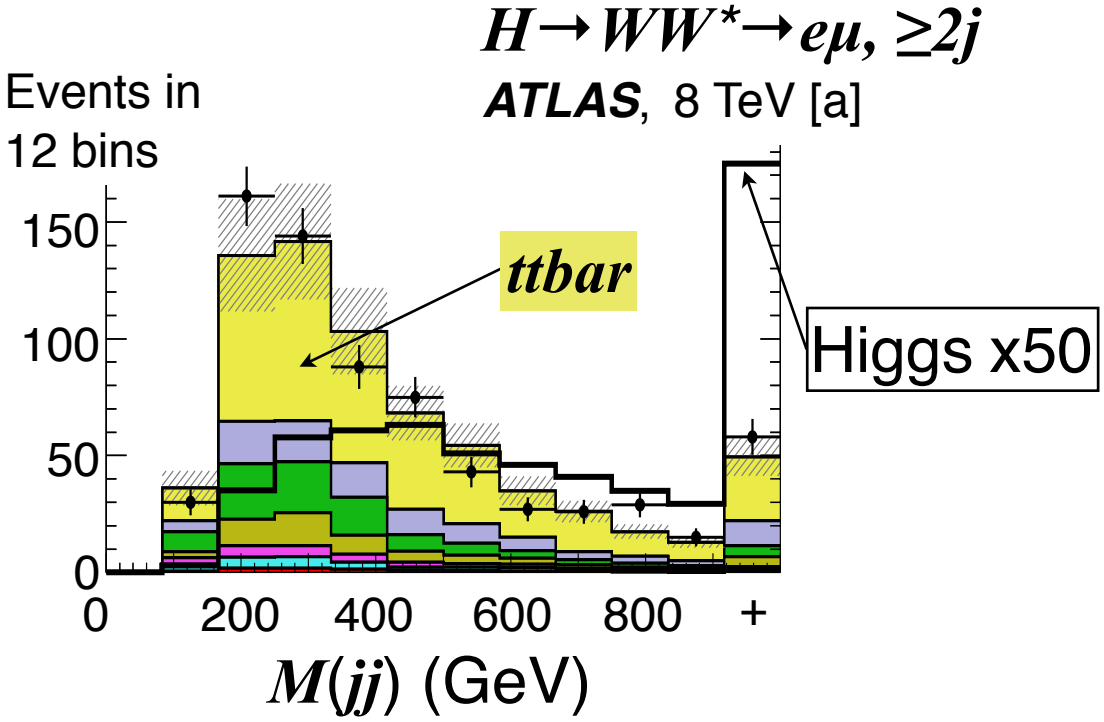
Physics of jj invariant mass

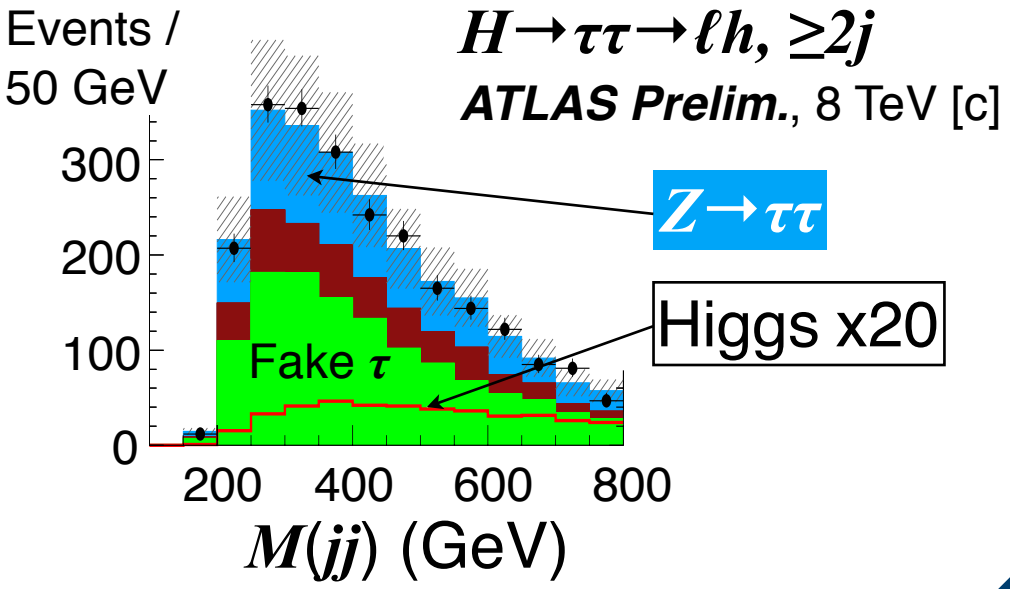
- More powerful than $\Delta\eta$ alone
- $M(jj) \approx \sqrt{P_{T1} \cdot P_{T2} \cdot e^{\Delta\eta}}$

  $\sim \langle P_{T,\,jet} \rangle\, e^{\Delta\eta\,/\,2}$
- Example: 40 • $e^{3/2}$ = 180 GeV

VBF has high value, non-VBF low

$M(jj)$ great v. all backgrounds





VBF central region in η

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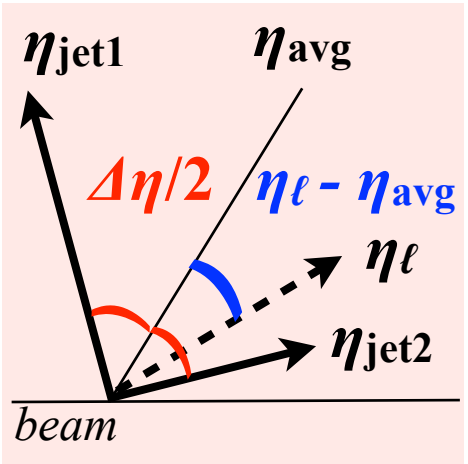
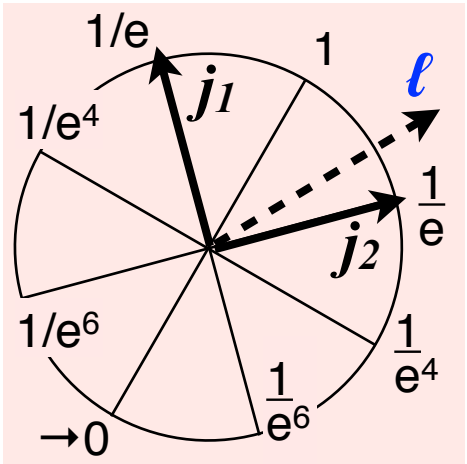
Quantify if object is in the central region

- Consider "centrality" of object w.r.t. VBF jets
- Example here takes lepton, but same for all

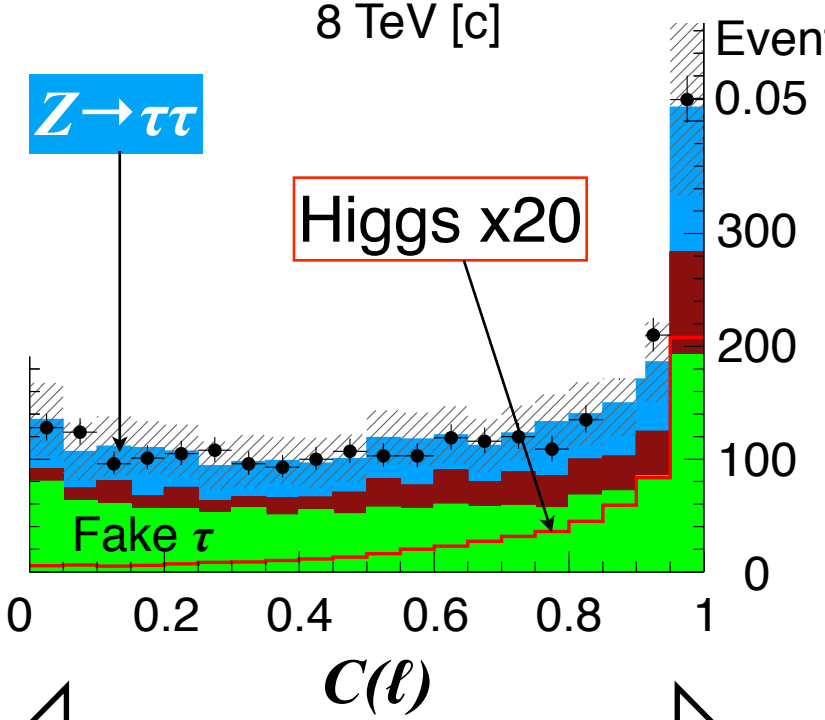




$H \to \tau\tau \to \ell h \geq 2j$

ATLAS Prelim.

8 TeV [c]



ℓ in between jets or not?

$$C(\ell) \equiv e^{-\left|\frac{\eta_\ell - \eta_{avg}}{\Delta\eta/2}\right|^2}$$

Non-VBF

VBF

Outline

Introduction

- Higgs via VBF

→ ATLAS at LHC

Focus on similar final states

- VBF $H \to WW^* \to e\,\mu$ $\nu_e\,\nu_\mu$
- VBF $H \to \tau\tau \to \ell\,h$ $\nu_\ell\,\nu_\tau\,\nu_\tau$

Missing E_T (MET)

2 lepton-like objects

Putting it together

ATLAS detector

2 magnets, 3 sub-detector groups

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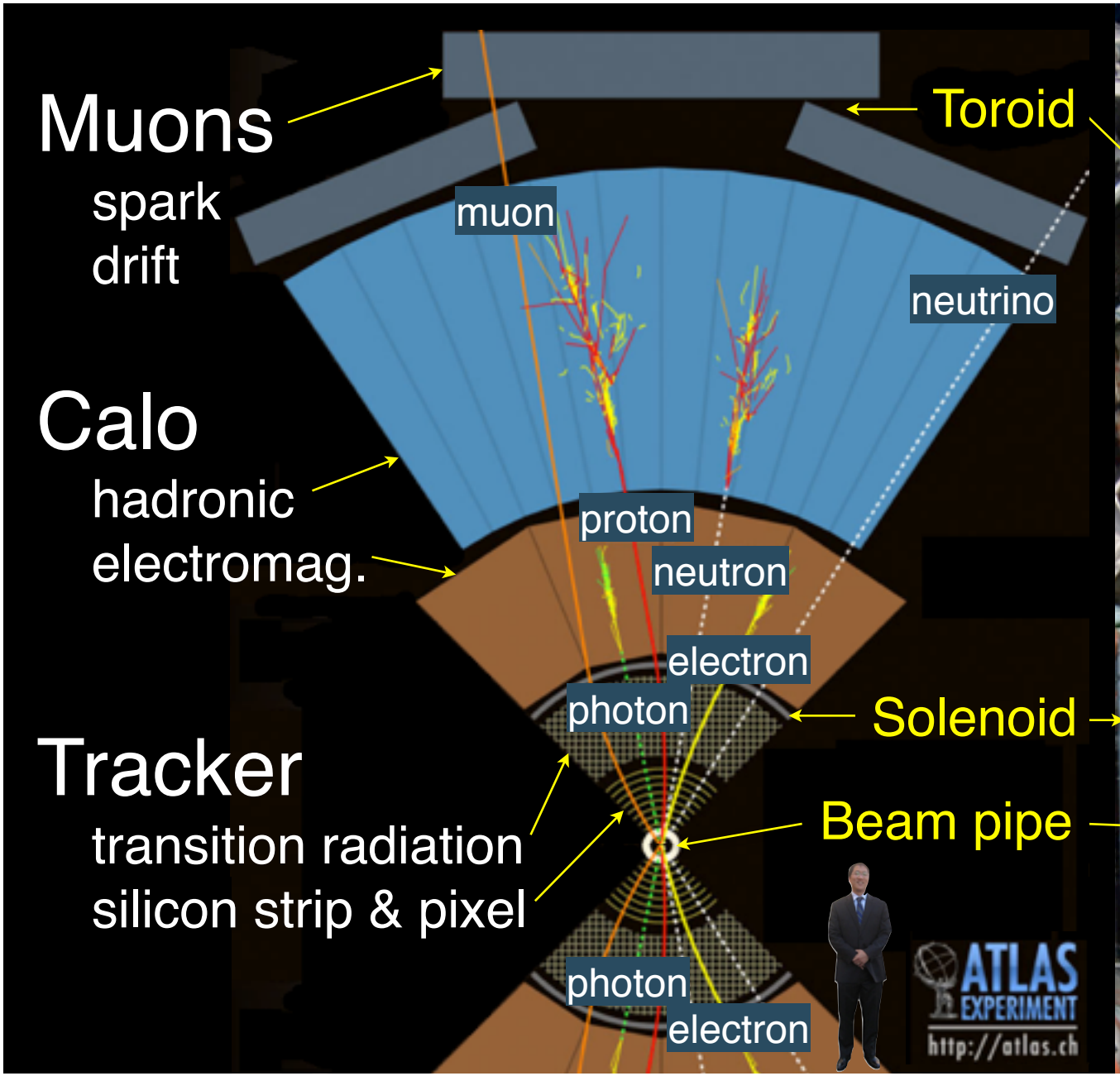

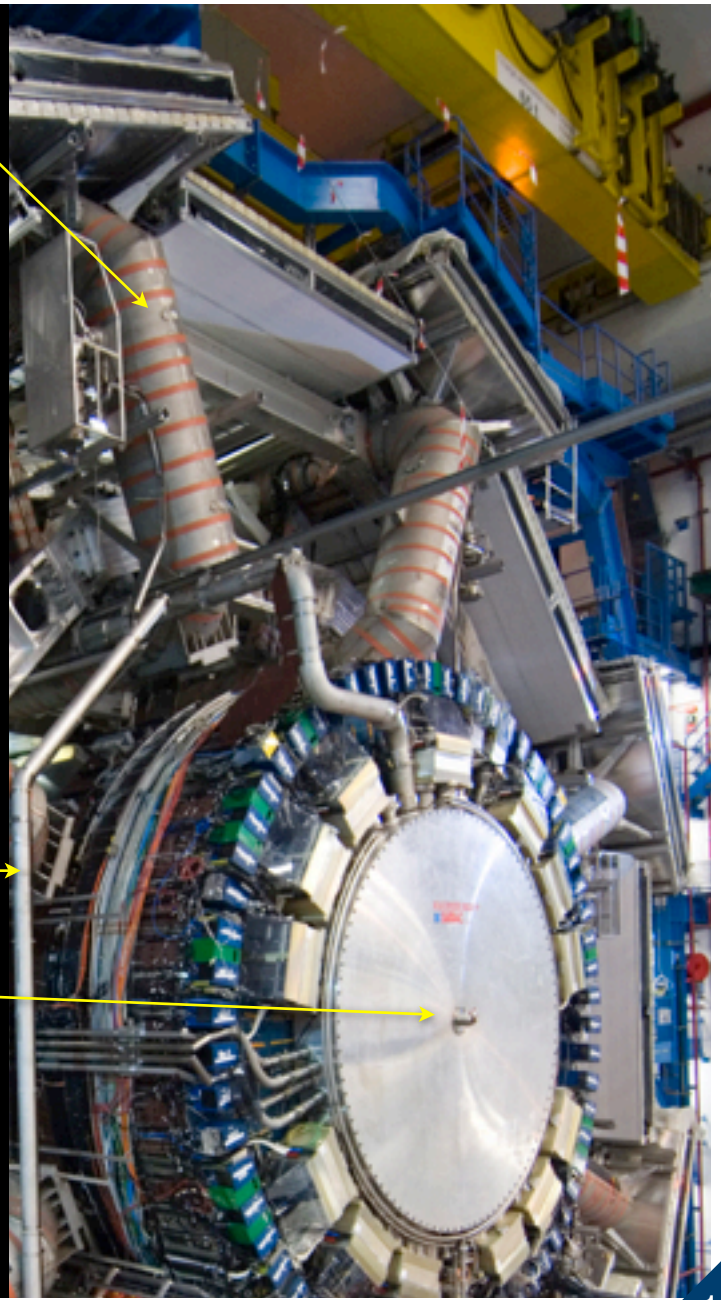

ATLAS η coverage

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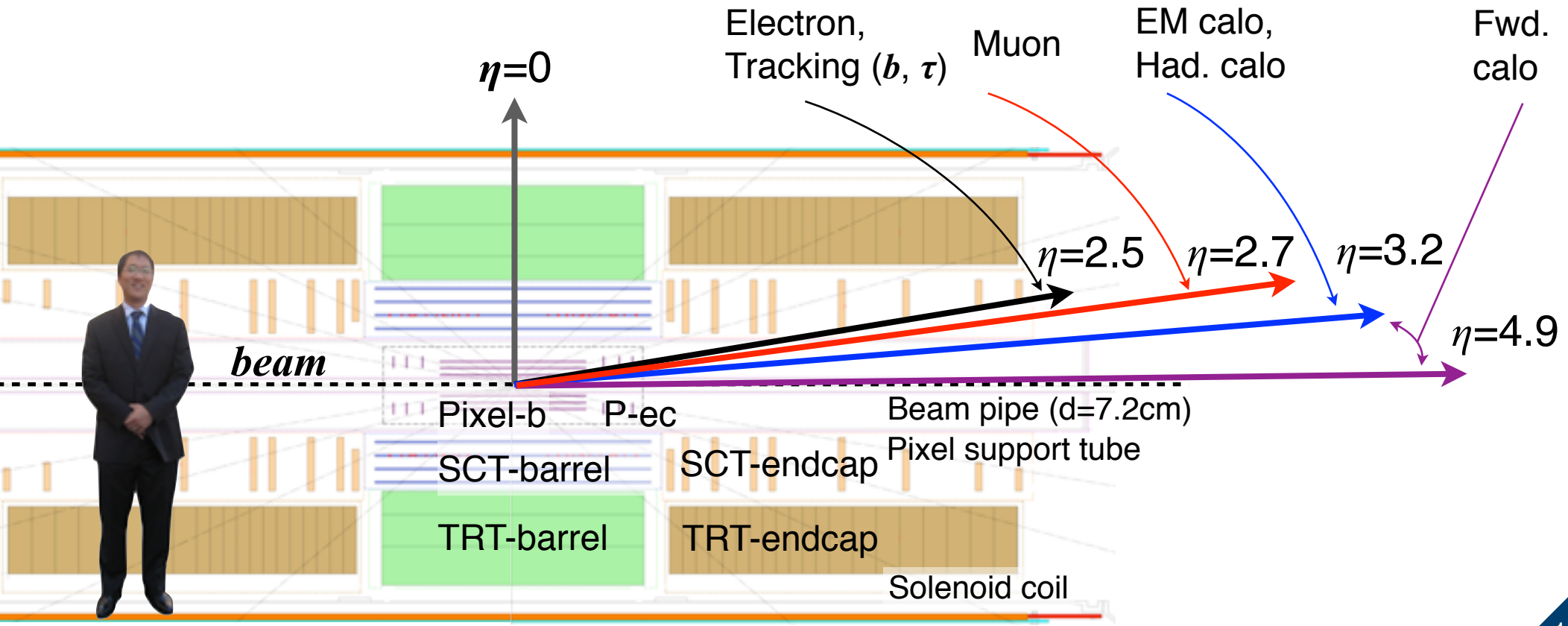
Shows tracker "inner detector"

Coverage important for analyses

- Lepton up to ~2.6
- Jet up to 4.5 → crucial to tag forward VBF jets
- Tracking up to 2.5 → limitation for *ttbar* rejection



b quark jets

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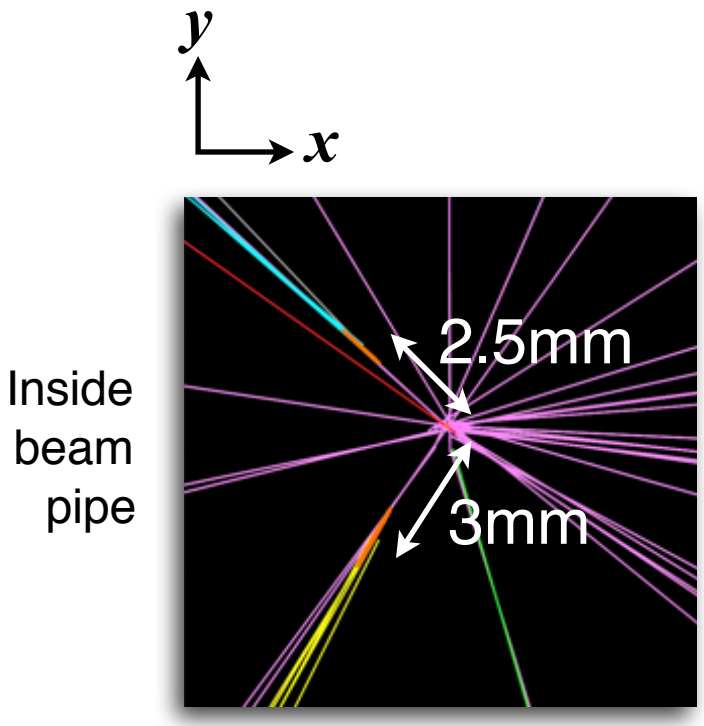
Long lifetime of **0.5mm**, displaced vertices



Data *ttbar* with two tagged *b*

Why *b* important

- Reject *ttbar* for $H \rightarrow WW^*$

Multivariate *b* identification

- 85% signal efficiency
- 10x rejection of light jets, 2.5x *c* jets

Hadronic τ "jets"

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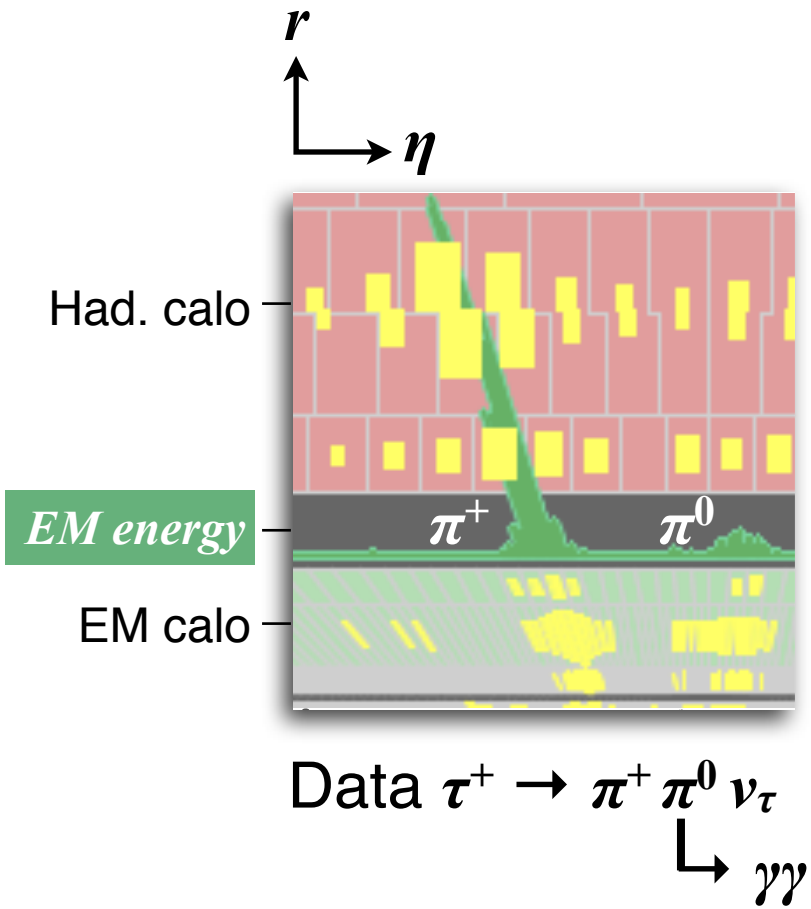
"Long" lifetime of $\mathbf{0.1mm}$, unique shower pattern



Why hadronic τ important

- $B(\tau \to h\nu_\tau) = 0.6$ for $H \to \tau\tau \to \ell h$

Multivariate τ identification

- 60% signal efficiency
- 20x rejection of light jets

ATLAS data

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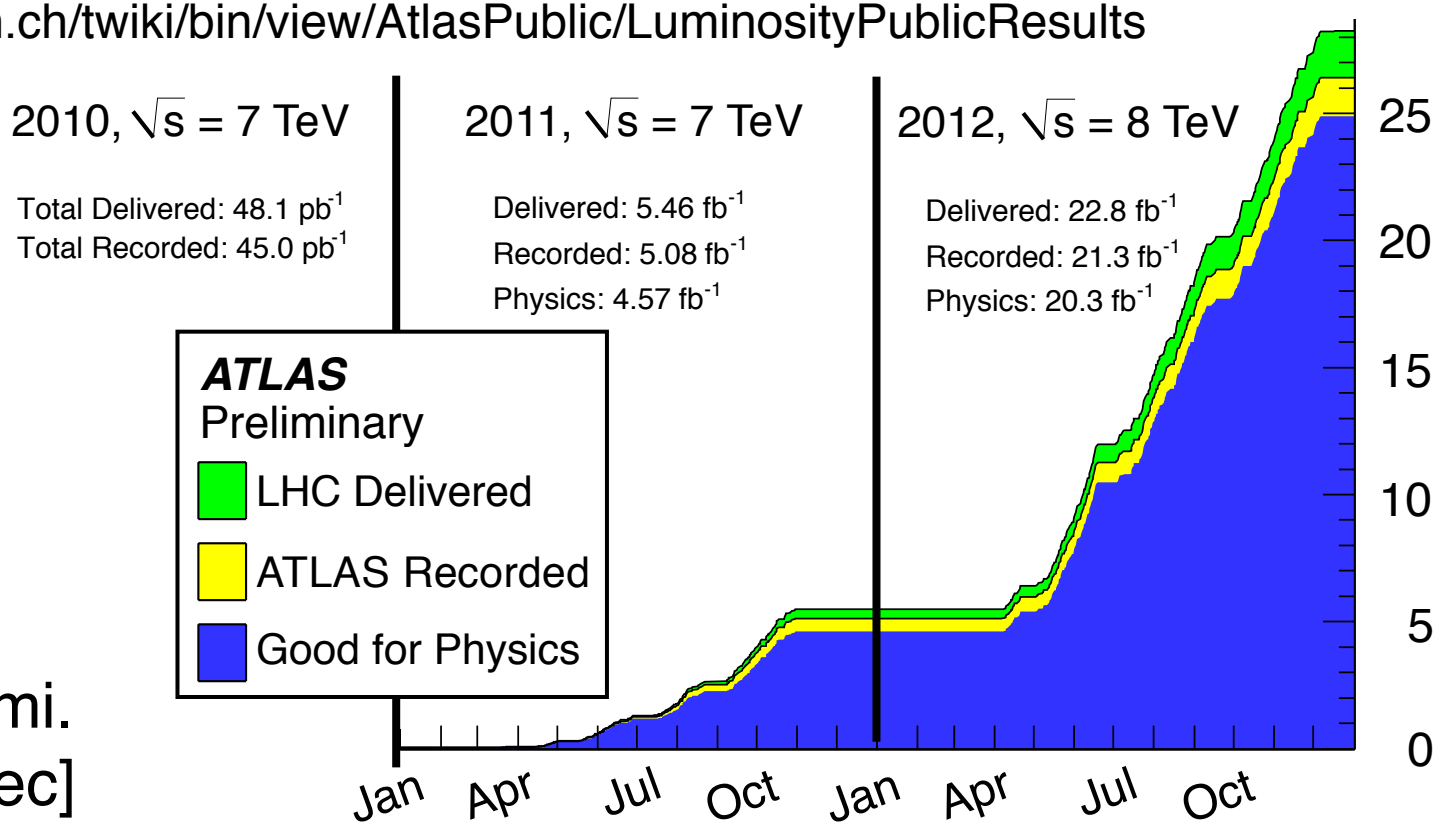
https://cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults

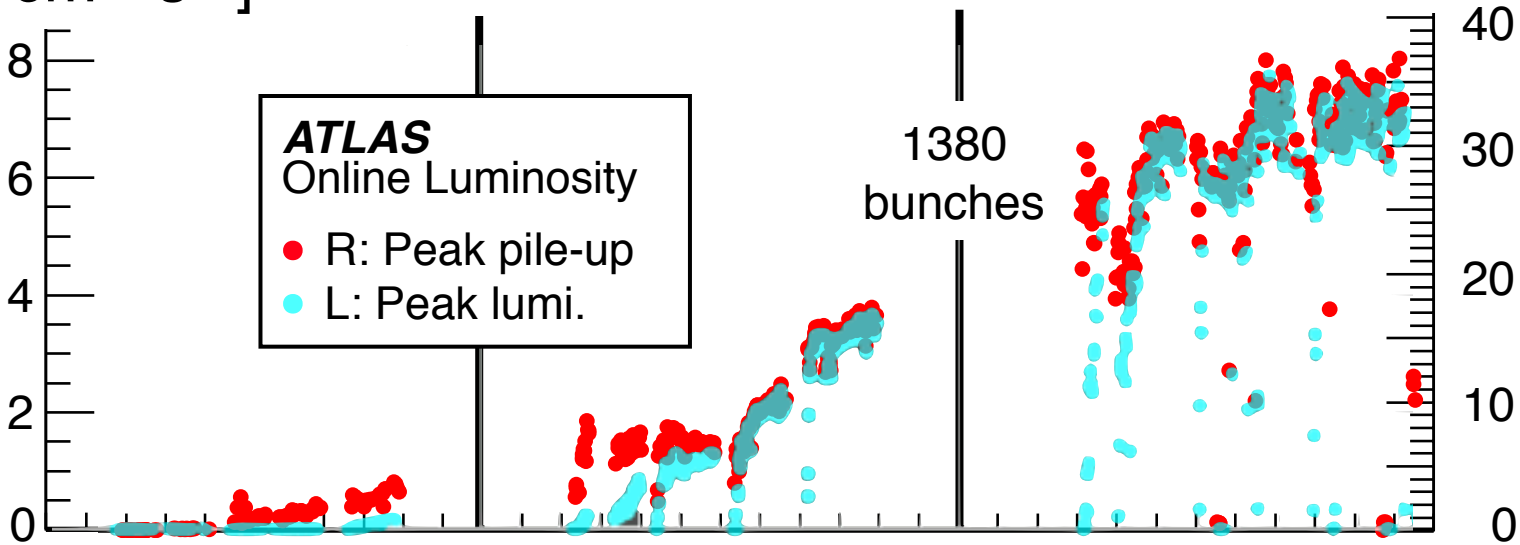


$\int L\,dt$

Integrated luminosity [fb^{-1}]

L_{peak}

Peak lumi. [nb^{-1} / sec] [10^{33} cm^{-2} s^{-1}]



$\langle\mu\rangle_{peak}$

Peak pp interactions per crossing

Event rates

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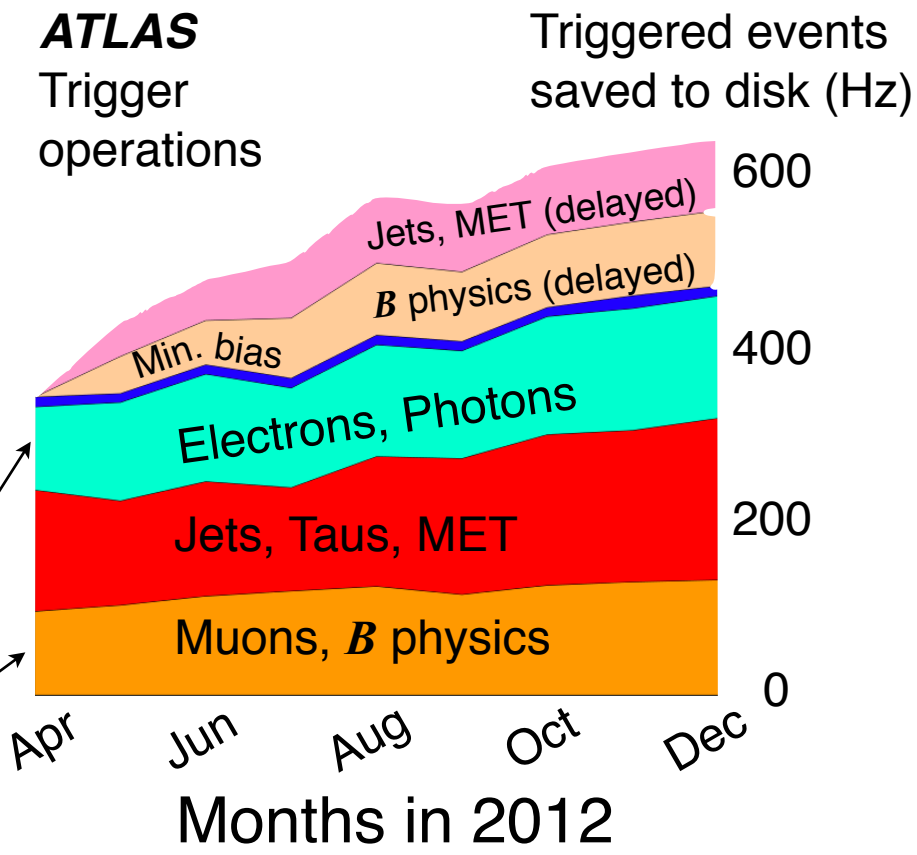
Production rates for $L_{peak} = 8\ \text{nb}^{-1}/\text{sec}$

- $\sigma_{\text{inelastic}} = 60$ mb $\rightarrow 5 \cdot 10^8$ /sec
- $\sigma_{Z \rightarrow \mu\mu} = 8$ nb $\quad 6$ /sec
- $\sigma_{gg \rightarrow H} = 20$ pb $\quad 0.2$ /sec
- $\sigma_{VV \rightarrow H} = 2$ pb $\quad 0.02$ /sec

Need large reduction of background while saving Higgs events

Analysis triggers

- VBF $H \rightarrow WW^* \rightarrow e\,\mu\ \nu_e\,\nu_\mu$
- VBF $H \rightarrow \tau\tau \rightarrow \ell\ h\ \nu_\ell\,\nu_\tau\,\nu_\tau$
- Both trigger on $\ell = e, \mu > 24$ GeV



How many Higgs did LHC make?

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Formula

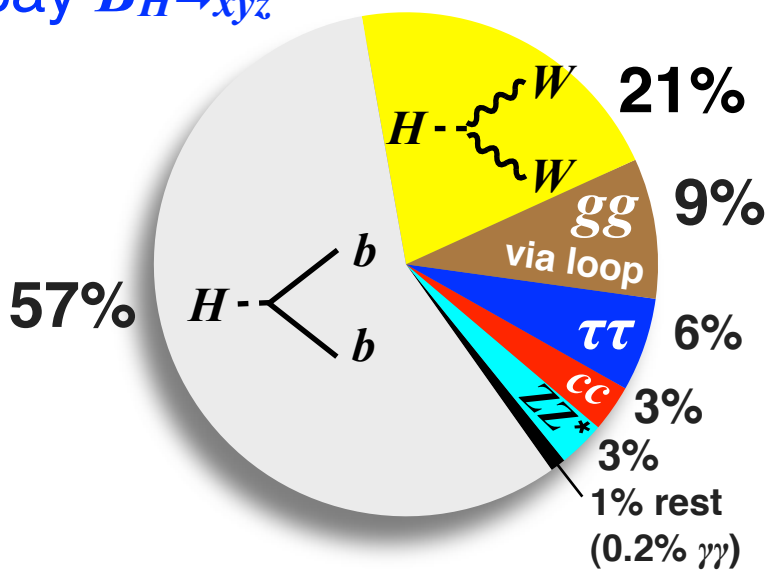
- $N_{pp\to H\to xyz} = L \cdot \sigma_{pp\to H} \cdot B_{H\to xyz}$

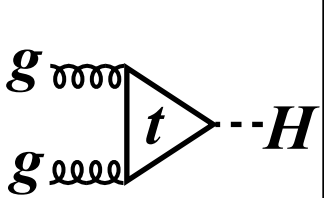
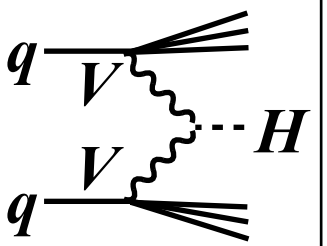
Production $\sigma_{pp\to H}$

Heinmeyer et al., CERN-2013-004

- ggF theory uncertainty ~10%
- VBF theory uncertainty ~ 3%
- VH, ttH smaller cross-section

Decay $B_{H\to xyz}$



	ggF	VBF
Diagram		
L (8 TeV)	21 fb^{-1}	
$\sigma_{pp\to H}$	19,270 fb	1,580 fb
$N_{pp\to H}$	400k	33k
$N_{H\to WW^*}$	90k	7k
$N_{H\to \tau\tau}$	25k	2k
$N_{WW^*\to e\mu}$	2k	200
$N_{\tau\tau\to \ell h}$	10k	800

O(1000) VBF Higgs in this talk

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- Higgs via VBF
- ATLAS at LHC

Focus on similar final states

→ VBF $H \to WW^* \to e\,\mu$ $\nu_e\,\nu_\mu$

- VBF $H \to \tau\tau \to \ell\,h$ $\nu_\ell\,\nu_\tau\,\nu_\tau$

Missing E_T (MET)

2 lepton-like objects

Putting it together

VBF $WW^* \rightarrow e\mu$

Hong

Analysis flowchart

Pre-sel.

- Require non-*b jets* with $\Delta\eta_{jj} \gtrsim 3$
- Require e, μ, MET

Analysis

- Select on VBF production properties
- Select on $H \rightarrow WW^*$ decay properties
- Background model validation

Results

- Fit $M_{T,\,\mathrm{Higgs}}$ to get $\mu_{\mathrm{Higgs,\,VBF}}$

Already discussed

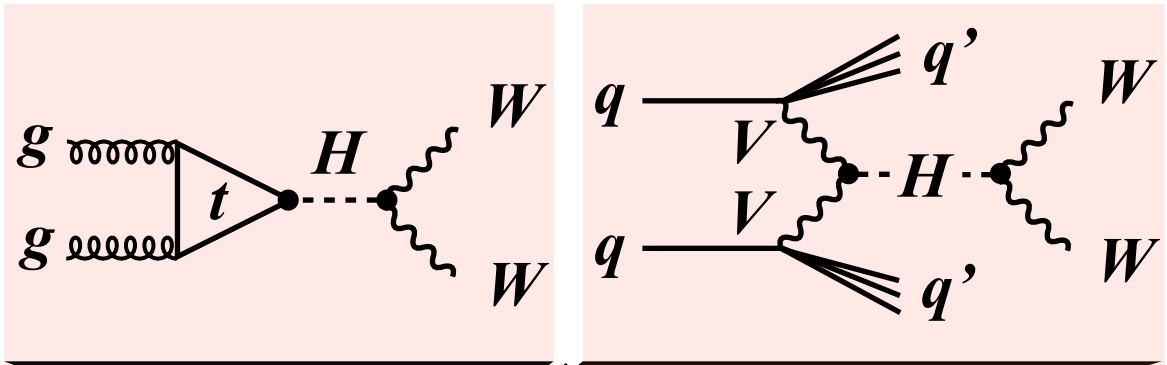
This section

Pre-sel.
Analysis
Results

WW^* physics with N_{Jet}

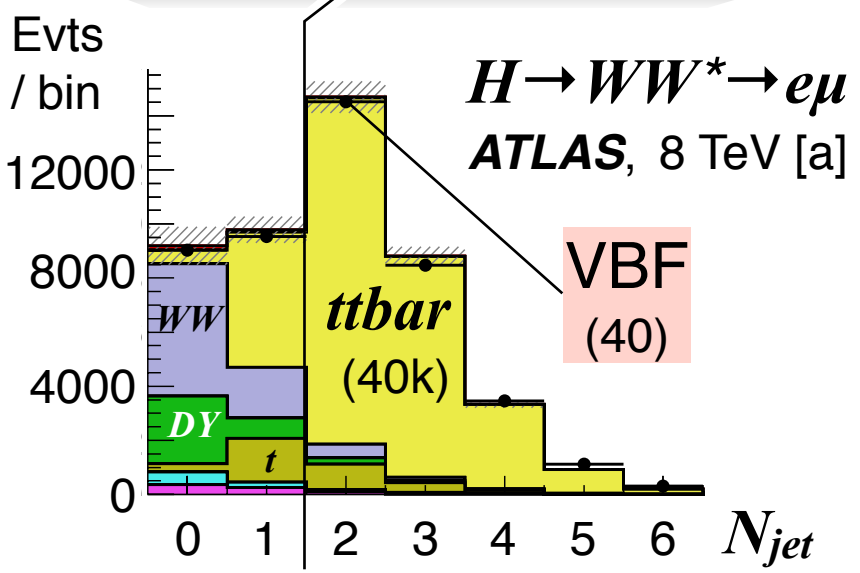
Hong

- Separate ggF v. VBF by N_{Jet}

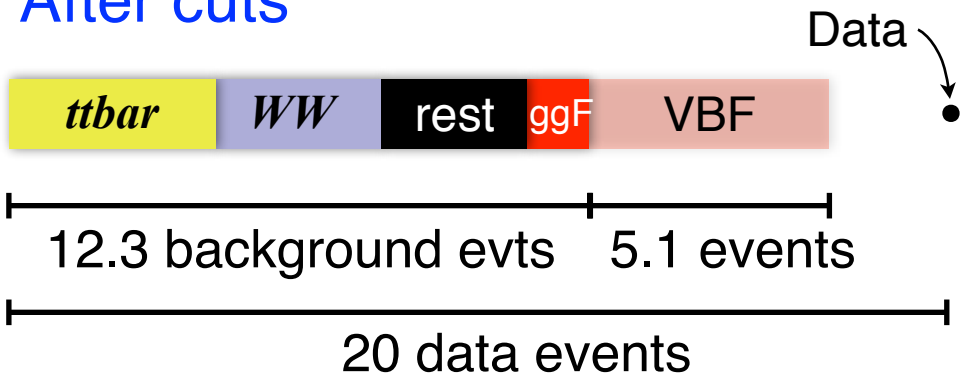


- Benefit by VBF rate $\propto |g_V|^4$
- Measuring ±50% rate translates to ±11% g_V

Before cuts (after pre-sel.)



After cuts



Two leptons, MET, jets (no b veto)

Great S/B

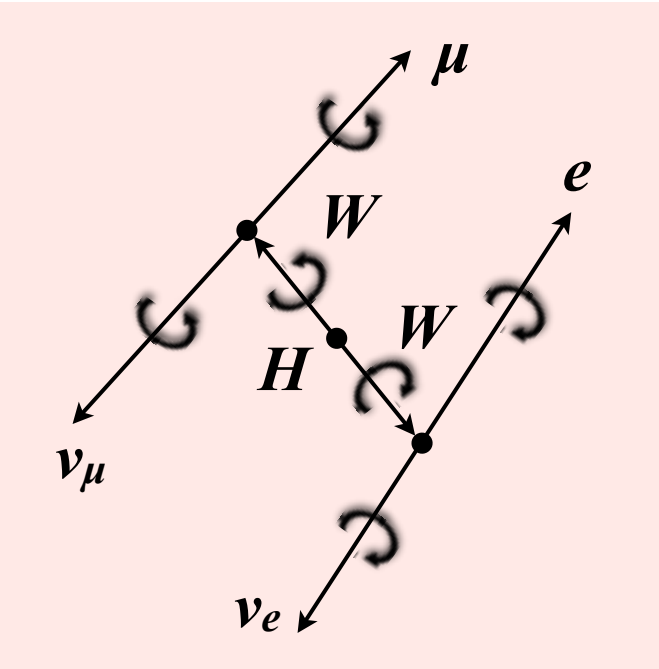
Pre-sel.
Analysis
Results

Physics with $\ell\ell$

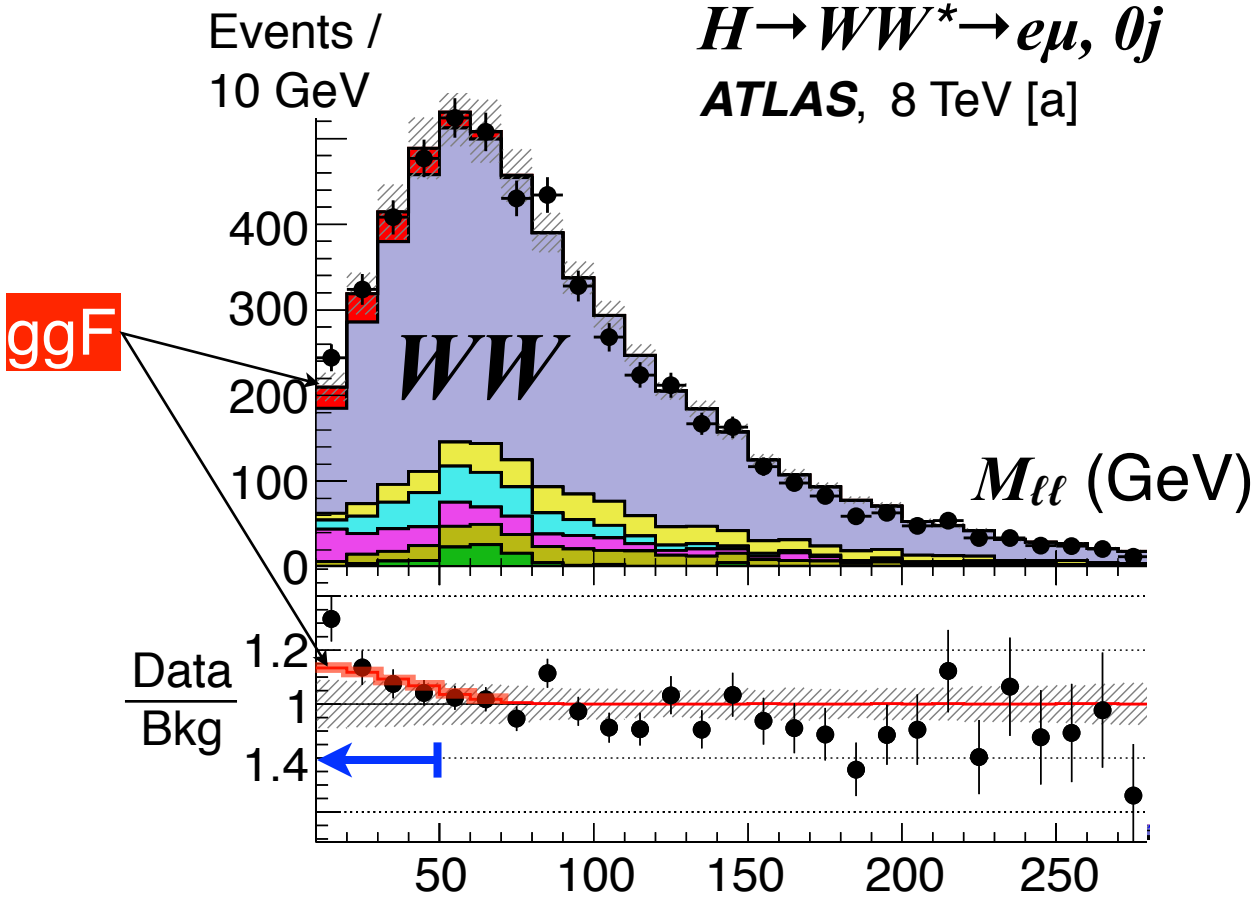
Hong

- Higgs ($J=0$)
- W decay violates parity
- Spin conservation

→ Collinear $\ell\ell$ → Low $M_{\ell\ell}$



Excess as expected



Pre-sel.

Analysis

Results

Physics with $\ell\ell$, MET

- Considered $\ell\ell$, now add MET
- Approximate mass with $M_{T,H}$
- Broad at ~ 30 GeV

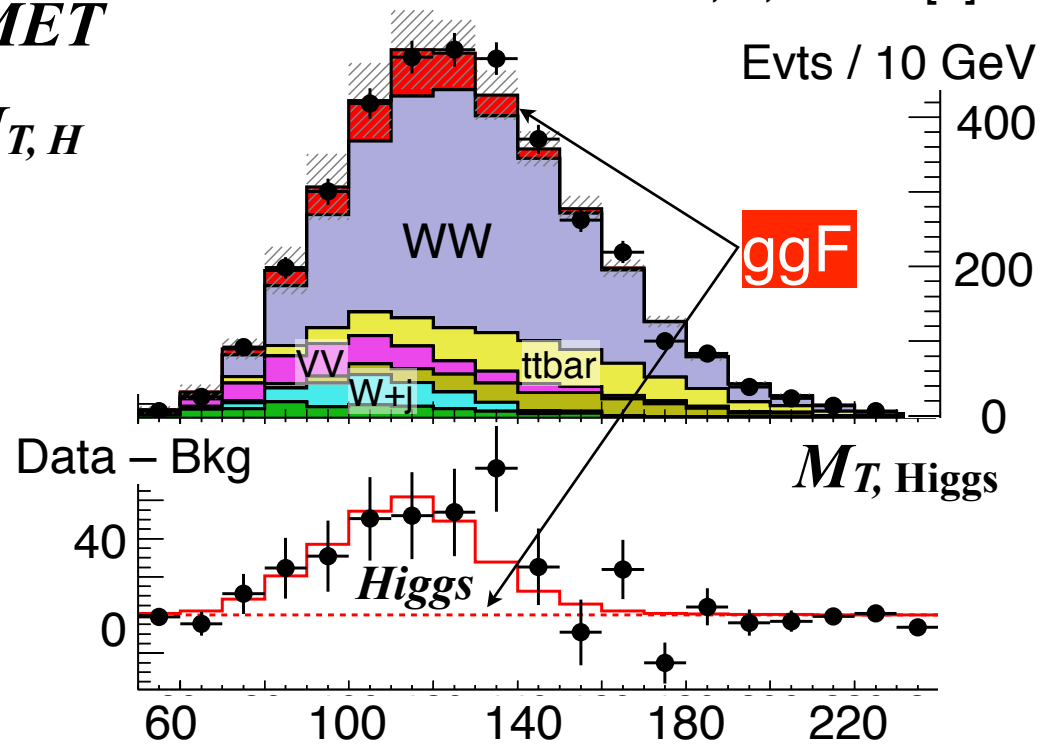
$$M_{T,H} = \sqrt{(E_{T,H})^2 - (\vec{P}_{T,H})^2}$$

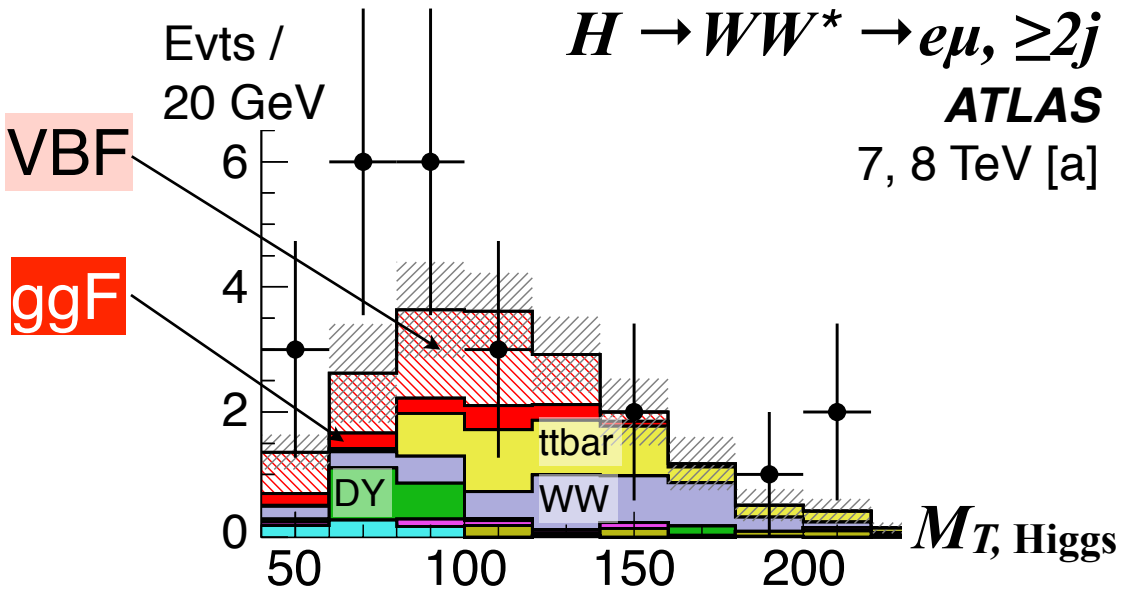
$$\vec{P}_{T,H} = \vec{P}_{T,\ell\ell} + \overrightarrow{MET}$$

$$E_{T,H} = E_{T,\ell\ell} + MET$$

$$\sqrt{(\vec{P}_{T,\ell\ell})^2 + (M_{\ell\ell})^2}$$

Shape, normalization consistent with Higgs at 125

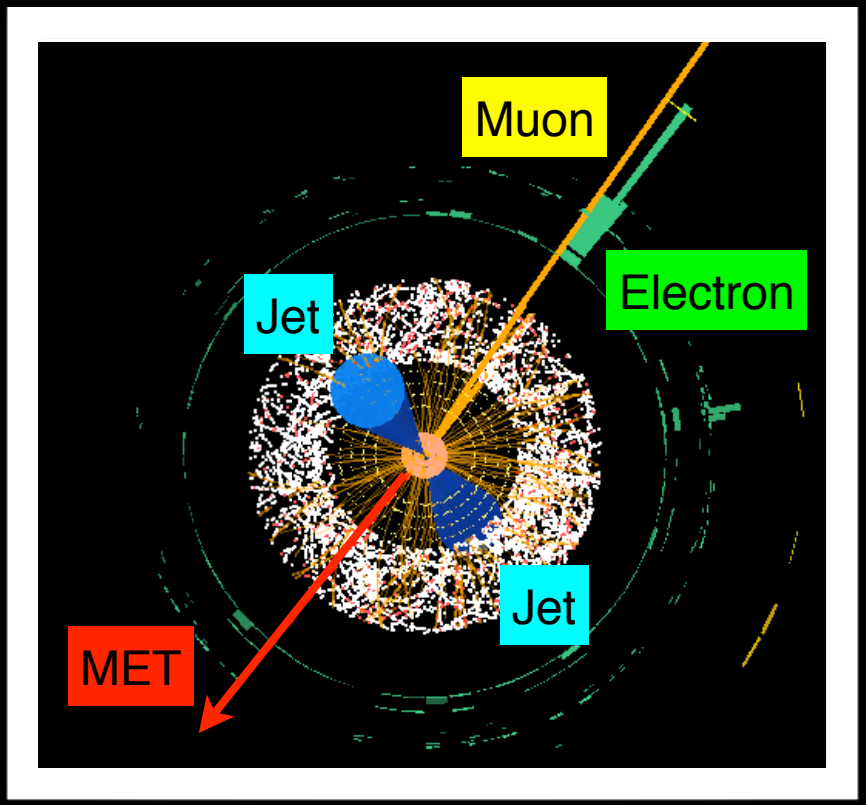


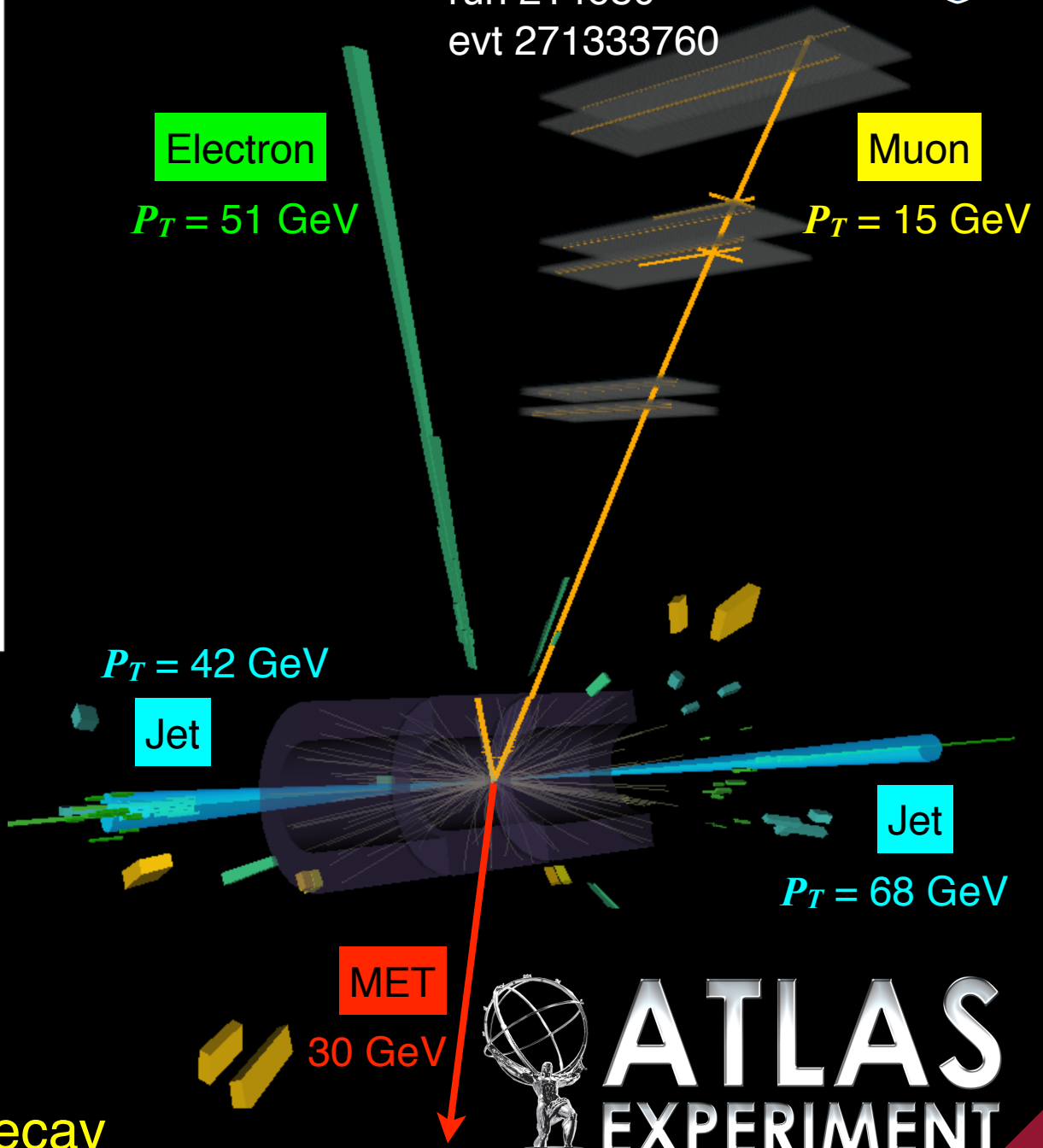


VBF $H \rightarrow WW^* \rightarrow e\mu$ MET

Nov. 17, 2012
07:42:05 CET
run 214680
evt 271333760

Hong





VBF ($\Delta\eta_{jj}$ = 6.6
M_{jj} = 1.5 TeV

HWW ($M_{e\mu}$ = 21 GeV
$M_{T,H}$ = 95 GeV

ttbar Jets not *b*-tagged

VBF-like in *jj* & Higgs-like in decay

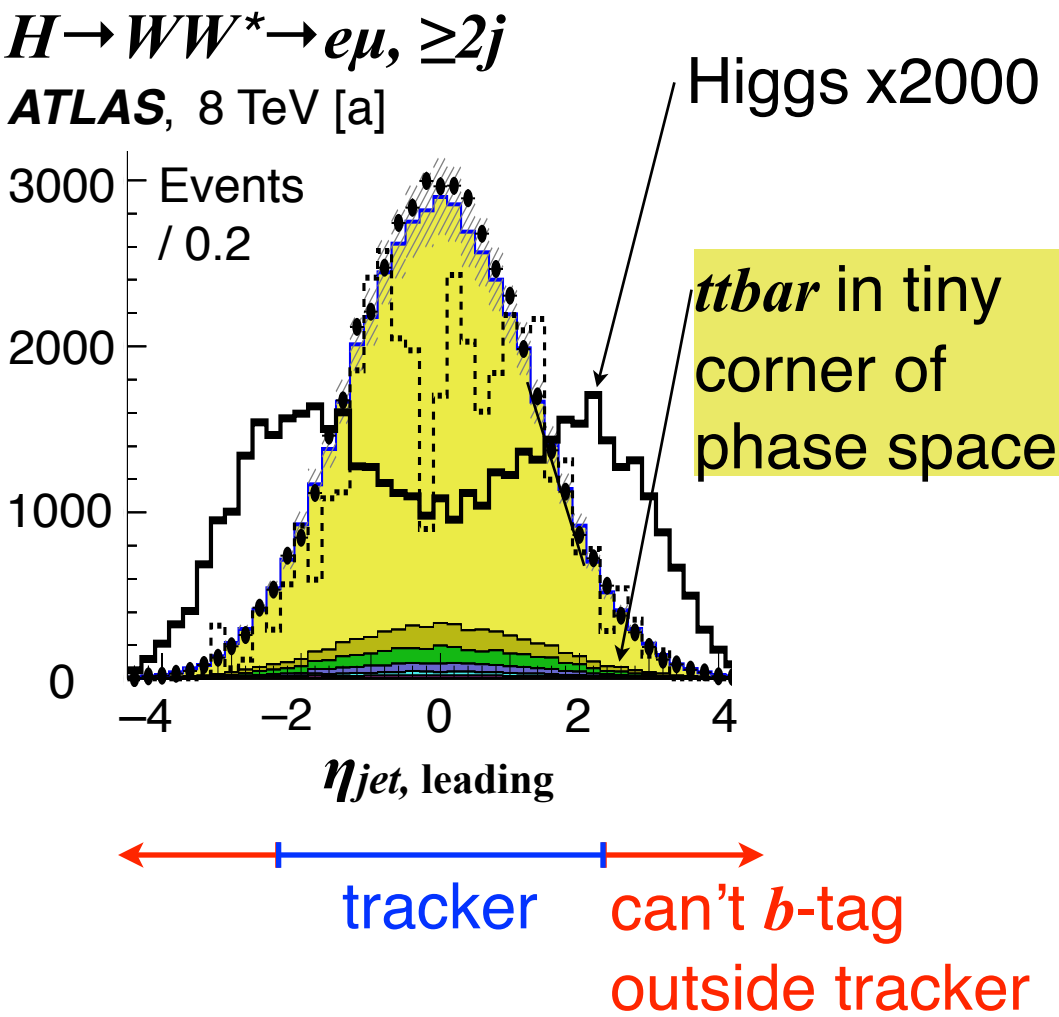
ATLAS EXPERIMENT

Pre-sel.
Analysis
Results

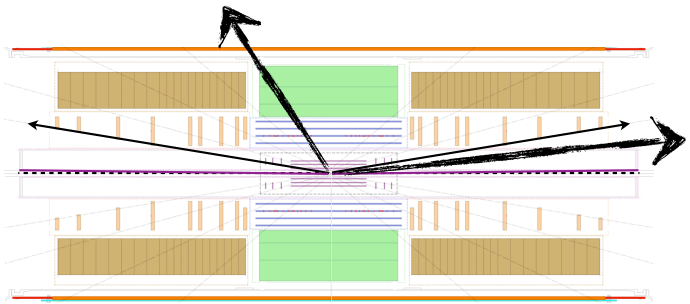
ttbar→*WbWb* background

Hong

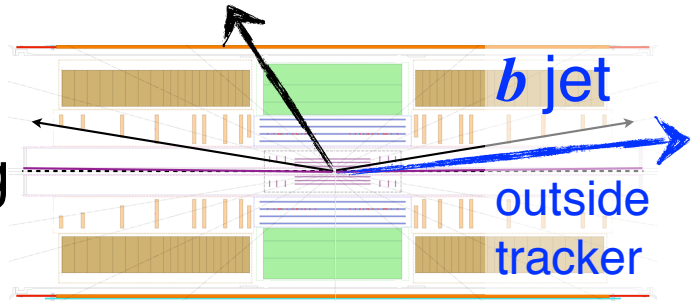
- VBF jets have large η, where no tracking
- In *ttbar* events, high M_{jj} selects one *b*, one non-*b*



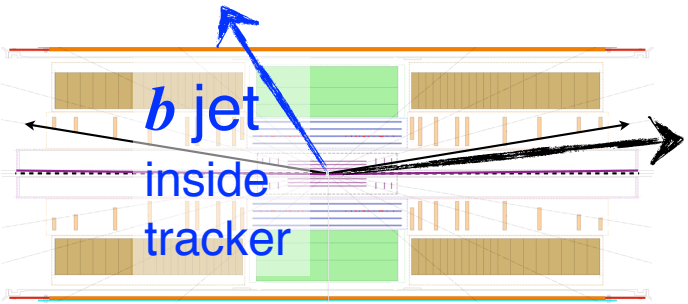
VBF Higgs



ttbar passing cuts



ttbar control sample



Pre-sel.
Analysis
Results

ttbar modeling difficulty

Hong

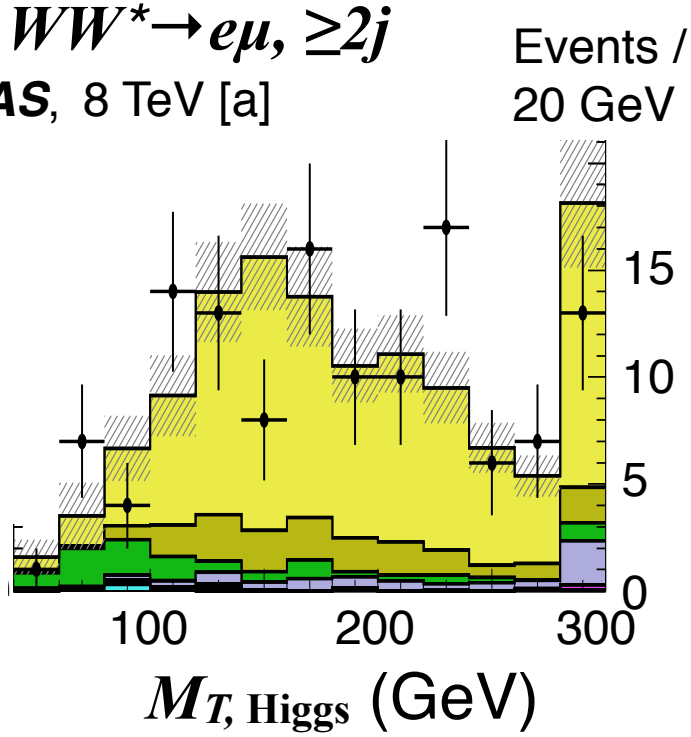
- Slide for experts

ttbar good $\ell\ell$ & *MET* modeling, but

ttbar control sample

$H \to WW^* \to e\mu$, $\geq 2j$

ATLAS, 8 TeV [a]



VBF jet modeling is difficult in tiny corner of phase space

- Estimate $N_{ttbar} = N_{\mathrm{MC}} \cdot f_{\mathrm{control}}$

  where $f_{\mathrm{control}} = \left(\frac{N_{\mathrm{Data}}}{N_{\mathrm{MC}}}\right)_{\mathrm{control}} = 0.6 \pm 0.15$

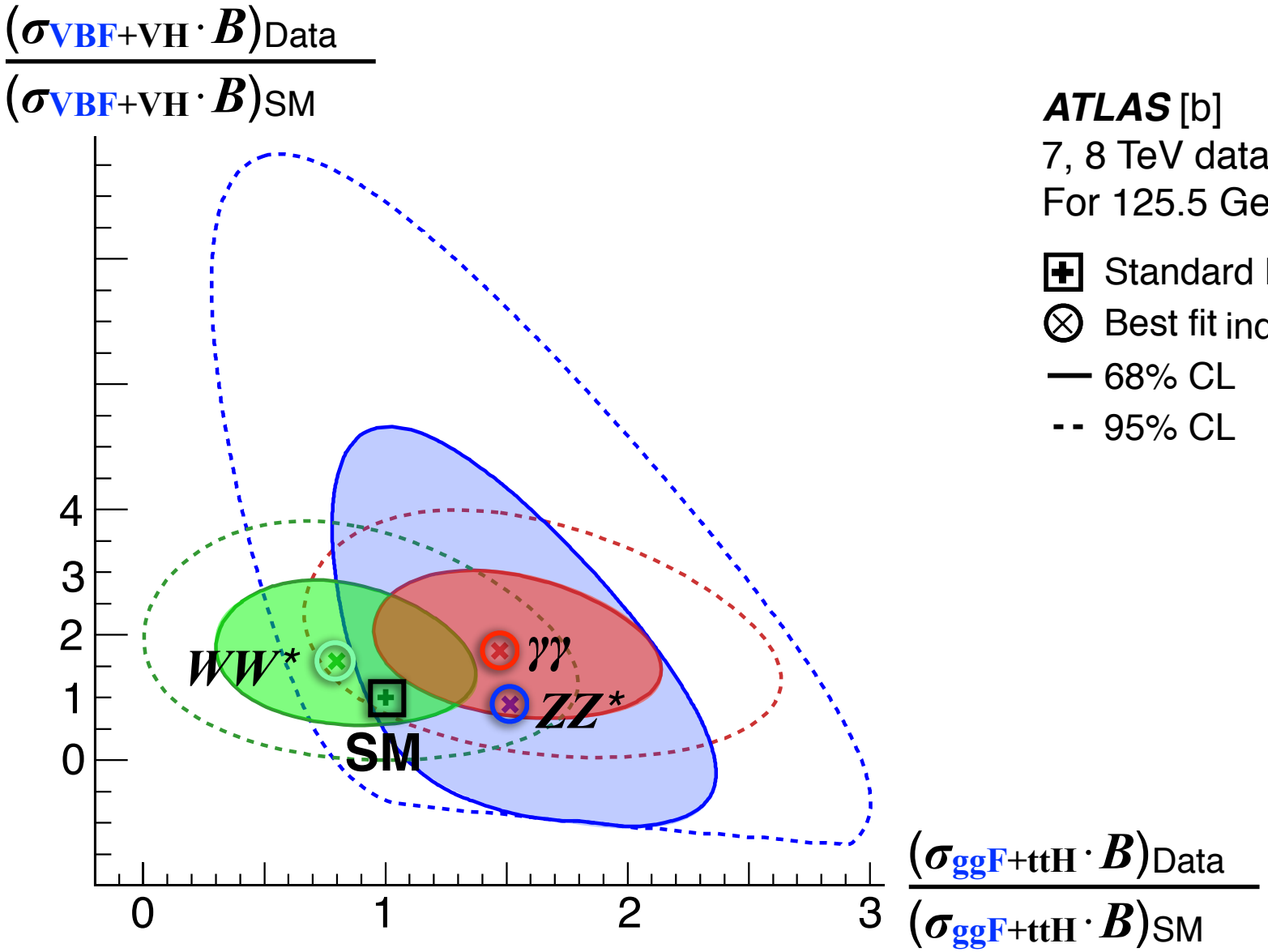
- Repeat with other MCs, find estimates consistent to 15%

ttbar estimate is stable

VBF v. ggF with bosons

Hong

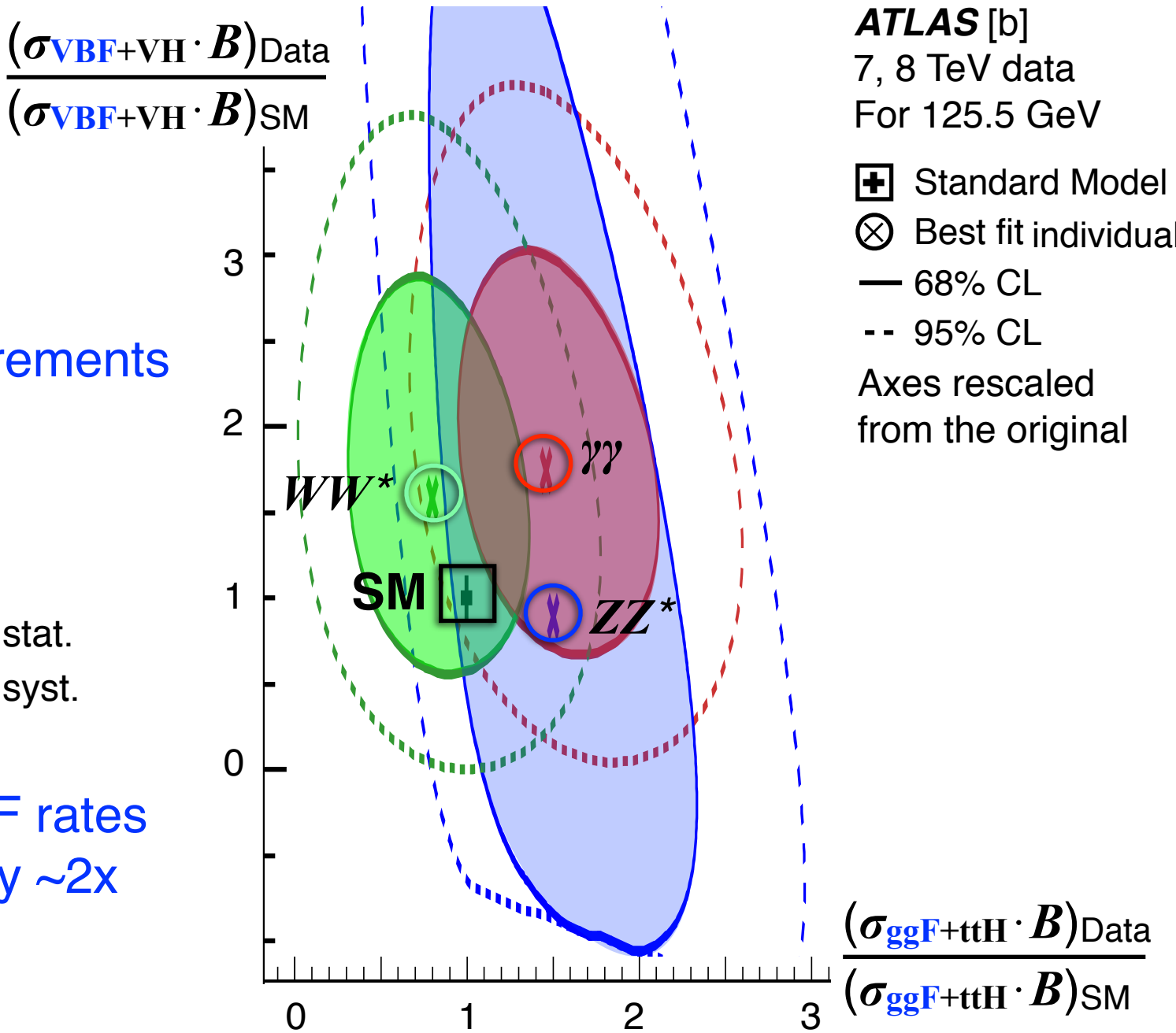
- VBF WW^* significance is 2.5σ, 1.6σ
  observed expected



Rescale the axes

so same metric in x, y

Hong



ATLAS [b]
7, 8 TeV data
For 125.5 GeV

- Standard Model
- Best fit individual
- 68% CL
- 95% CL

Axes rescaled from the original

VBF WW^* measurements

- $\frac{\mu_{VBF}}{\mu_{ggF}} = 2.0 \pm {}^{2.2}_{1.0}$
- $\mu_{VBF} = 1.6 \pm 0.8$

  40% stat.

  25% syst.

For all modes, ggF rates better than VBF by ~2x

Evidence of VBF

in boson final states

ATLAS [b]
For 125.5 GeV
7, 8 TeV data

Hong

Combine WW^*, ZZ^*, $\gamma\gamma$

- VBF evidence at 3.3σ
- $\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.4 \pm {}^{0.4}_{0.3}\,(\text{stat}) \pm {}^{0.6}_{0.4}\,(\text{syst})$

$$= 1.4 \pm {}^{0.7}_{0.5}$$

Measured ggF, VBF with bosons

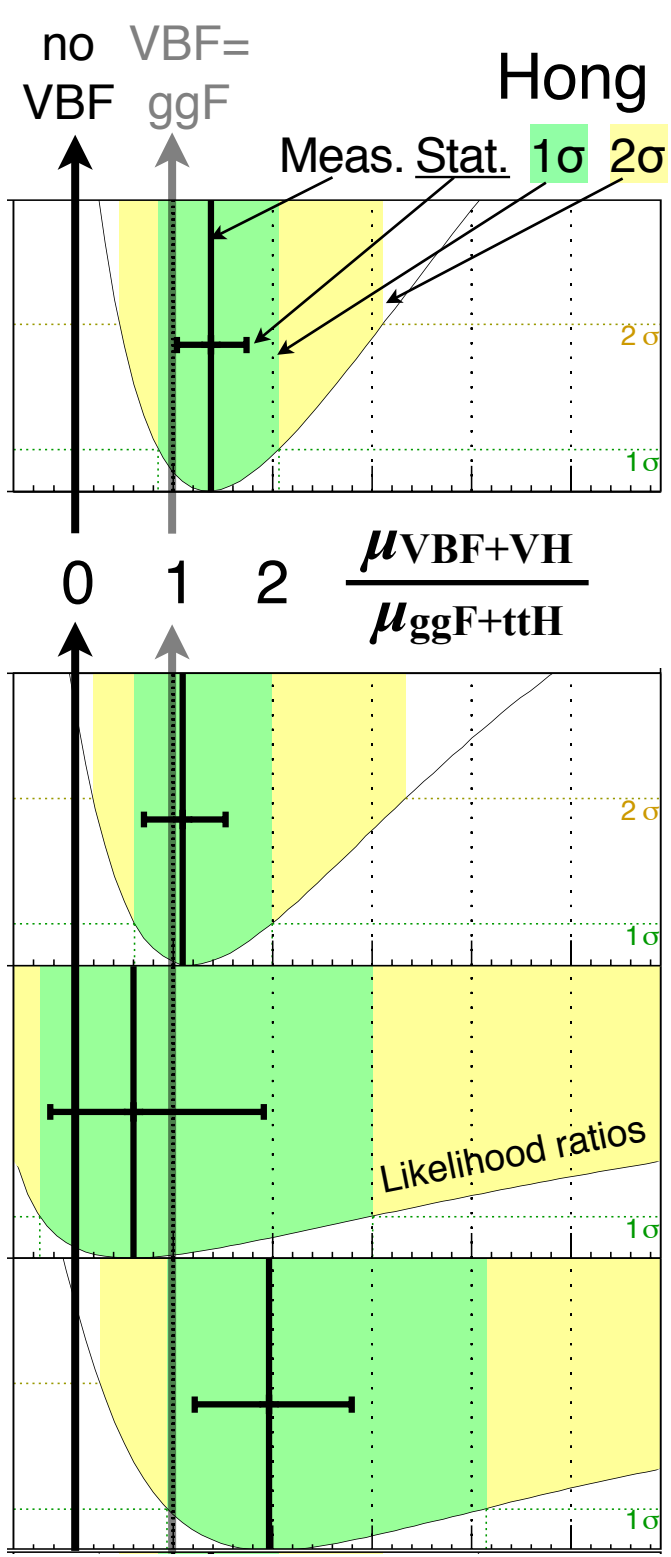
What about fermions?

Combined

$H \to \gamma\gamma$

$H \to ZZ^*$

$H \to WW^*$



Outline

Introduction

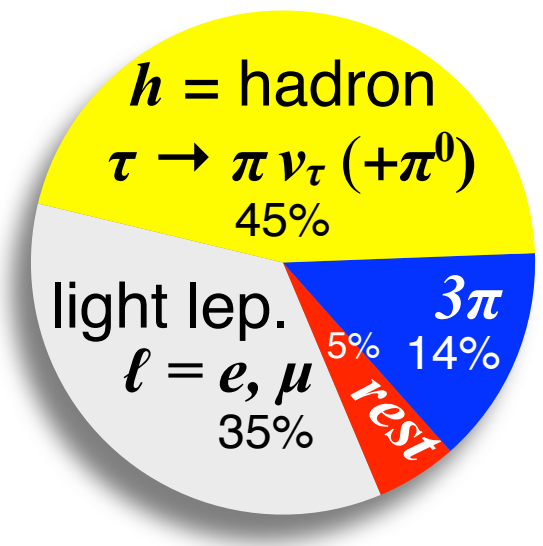
- Higgs via VBF
- ATLAS at LHC

Focus on similar final states

- VBF $H \rightarrow WW^* \rightarrow e\,\mu$ $\nu_e\,\nu_\mu$
- → VBF $H \rightarrow \tau\tau \rightarrow \ell\,h$ $\nu_\ell\,\nu_\tau\,\nu_\tau$

Missing E_T (MET)

Putting it together



VBF $\tau\tau \rightarrow \ell h$

Hong

Analysis flowchart

- Trigger on ℓ

Pre-sel.

- Require non-b *jets* with $\Delta\eta_{jj} > 3$
- Require ℓ, $\tau \rightarrow h$, *MET*

Analysis

- Define variables for VBF production
- Define variables for $H \rightarrow \tau\tau$ decay
- Train BDT to select H using all vars
- Background model validation

Results

- Fit *BDT score* to get μ_{Higgs}

Already discussed

This section

Pre-sel. → Analysis → Results

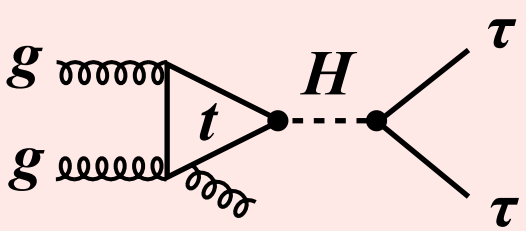
$\tau\tau$ physics with N_{Jet}

Hong

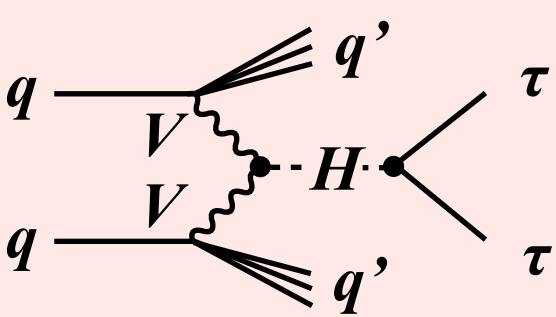
- Like WW^*: have ggF, VBF

yes	better S/B	WW^*
good	best	$\tau\tau$

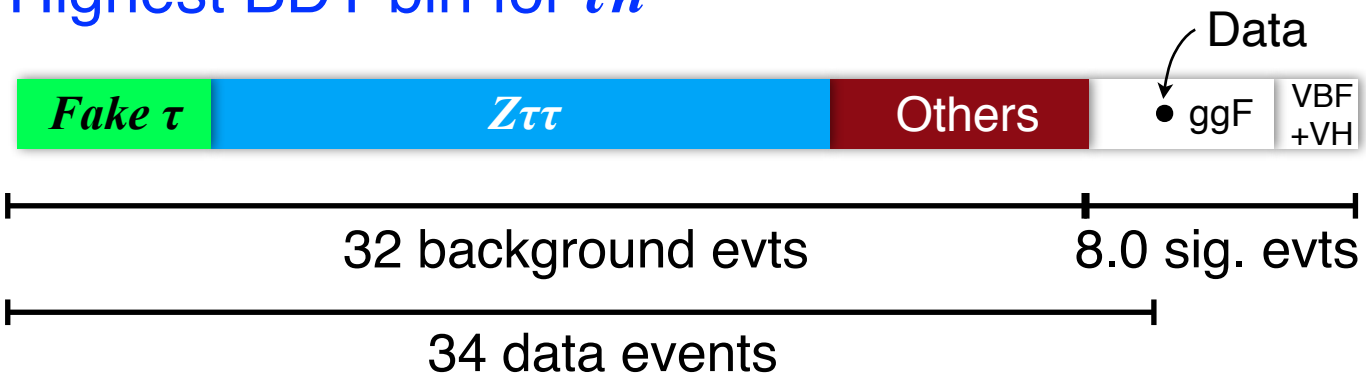
Rate $\propto |g_F|^2$

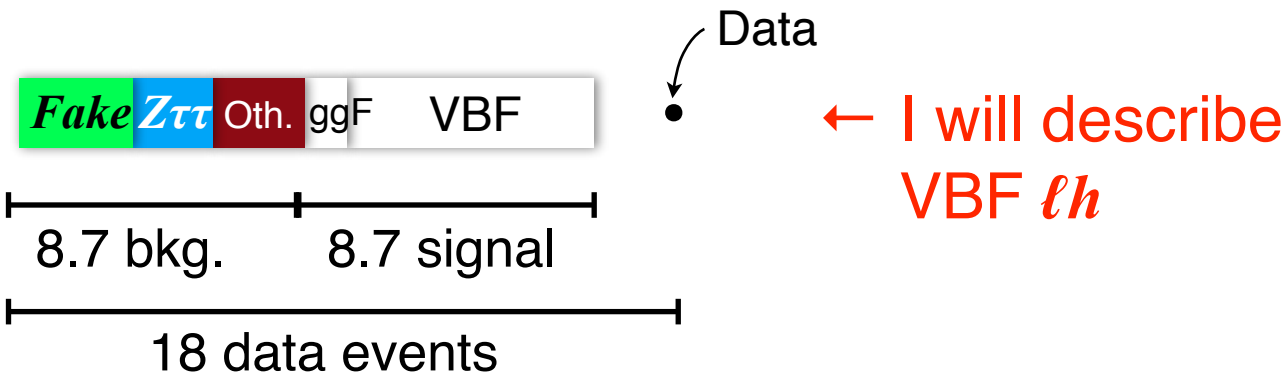


"boosted" ($P_{T,H}$>100)



Highest BDT bin for ℓh





← I will describe VBF ℓh

Pre-sel.

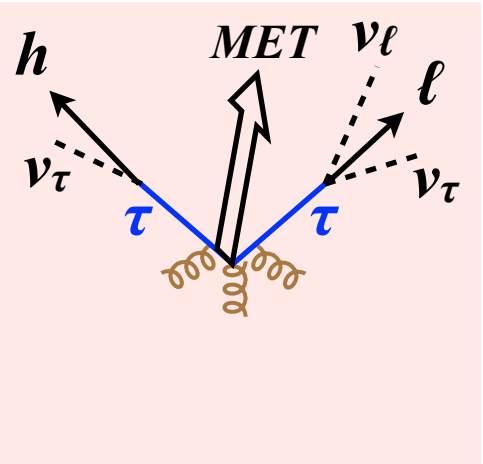
Analysis

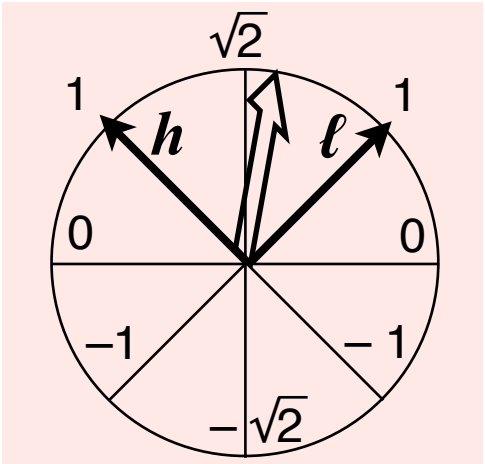
Results

Suppress fake $\tau\tau$ with φ_{MET}

Hong

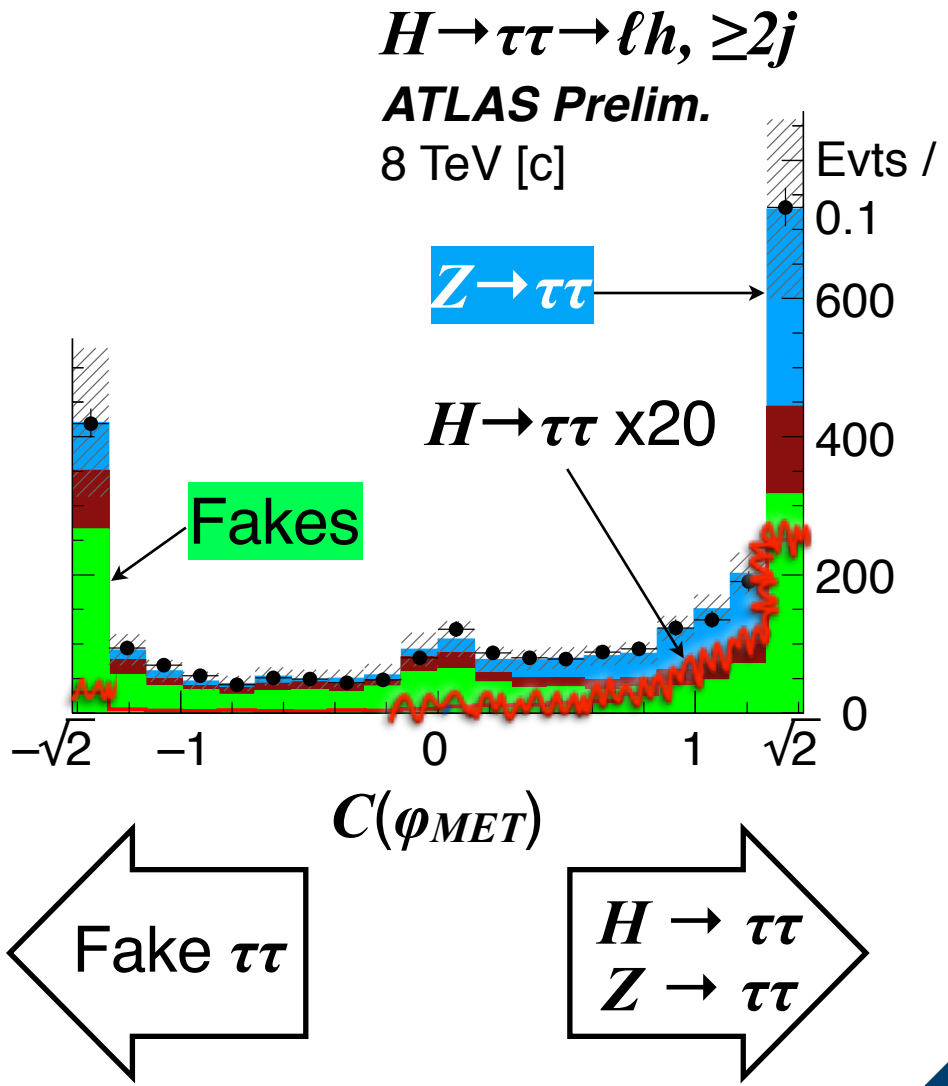
- Neutrinos from τ decays are mostly collinear
- Define "centrality" of φ_{MET} w.r.t. charged daughters





ν along ℓ, so $\overrightarrow{MET}$ in between

Construct a metric w.r.t. ℓ, h

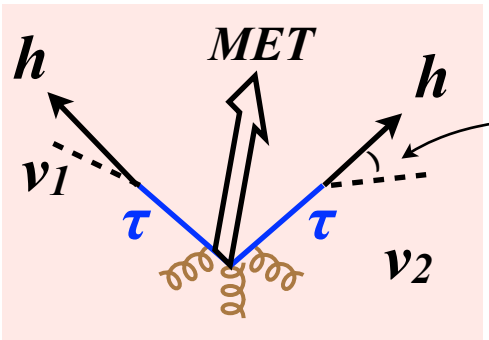


Good separation from fake $\tau\tau$

Pre-sel.
Analysis
Results

Suppress $Z \to \tau\tau$ with $M(\tau\tau)$

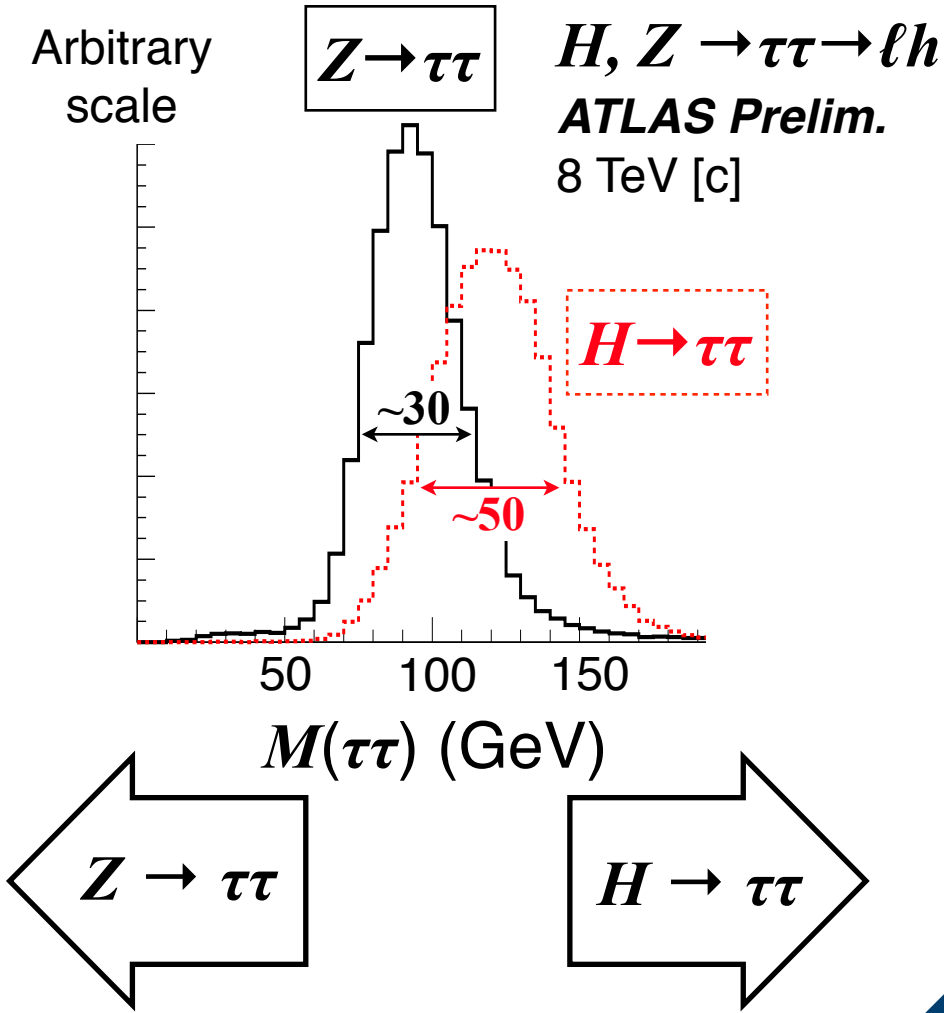
- $M(\tau\tau) = M(\ell h \nu_e \nu_\tau \nu_\tau)$, so need $\vec{P}_{\nu 1}$, $\vec{P}_{\nu 2}$, $\vec{P}_{\nu 3}$
- $MET_{x,y} = (\Sigma_i \vec{P}_{\nu,i})_{x,y}$ resolution smears constraint
- Parametrize unknowns by opening angles $\Delta\rho$



A. Elagin *et al.*, NIM A654 (2011) 481

1. Generate $\Delta\rho$ distributions with MC
2. Scan allowed configurations, pick most likely $M(\tau\tau)$ for each event

Good separation from $Z \to \tau\tau$



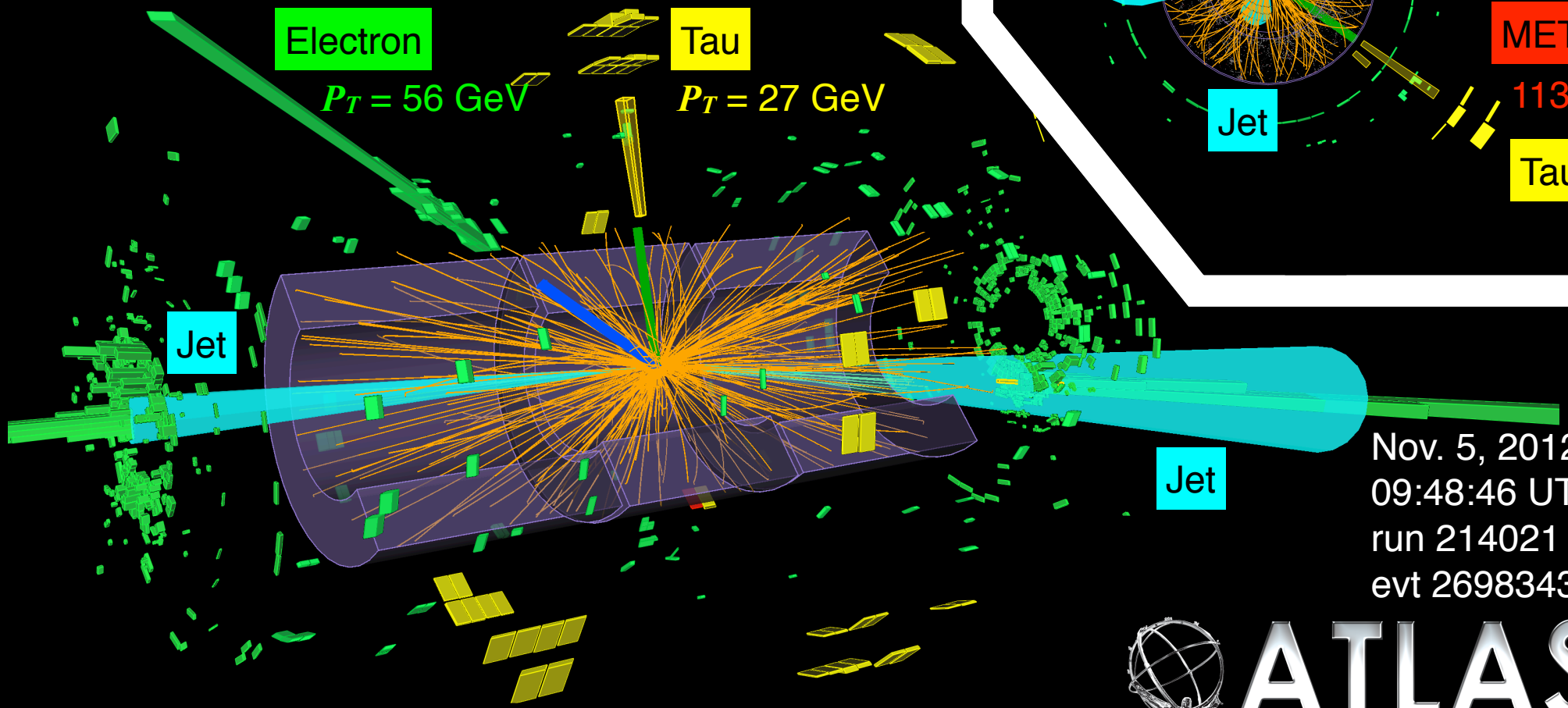
VBF $H \rightarrow \tau\tau \rightarrow eh\ MET$

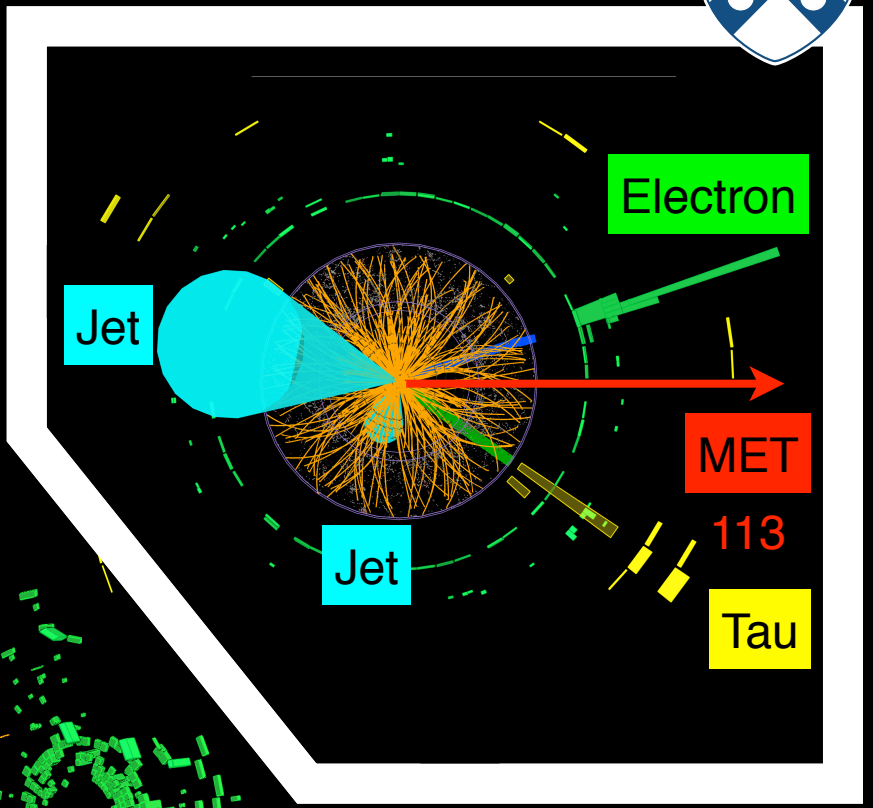
Hong

VBF - M_{jj} = 1.5 TeV

$H\tau\tau$ - $M_{\tau\tau}$ = 129 GeV

BDT score = 0.99, S/B here is 1.0





Nov. 5, 2012
09:48:46 UTC
run 214021
evt 269834309

VBF-like in *jj* & Higgs-like in decay

ATLAS EXPERIMENT

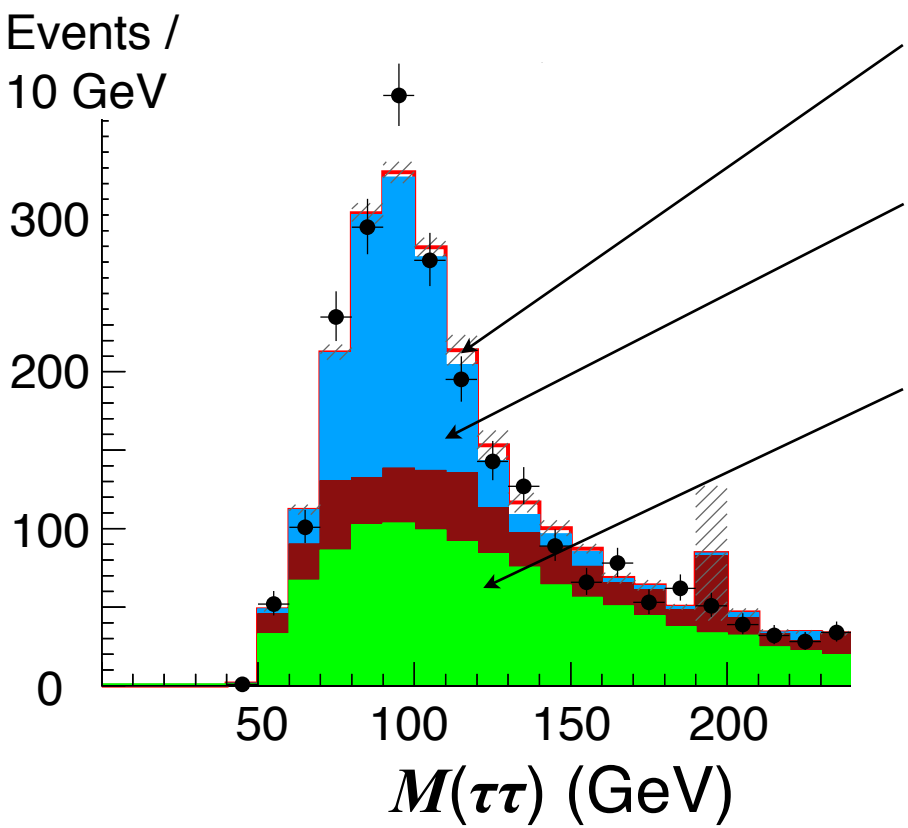
Pre-sel.
Analysis
Results

Train BDT to select Higgs

- Feed BDT the variables for VBF production, H decay
- I described the key ones already
- Let's look at $M(\tau\tau)$ before applying BDT

$H \to \tau\tau \to \ell h$, $\geq 2j$

ATLAS Prelim., 8 TeV [c]



$H \to \tau\tau$ is visible (note y-axis)

$Z \to \tau\tau$ is falling - use $\mu\mu$ sample

Fake τ is flatter - "fail" sample

These are estimated using data

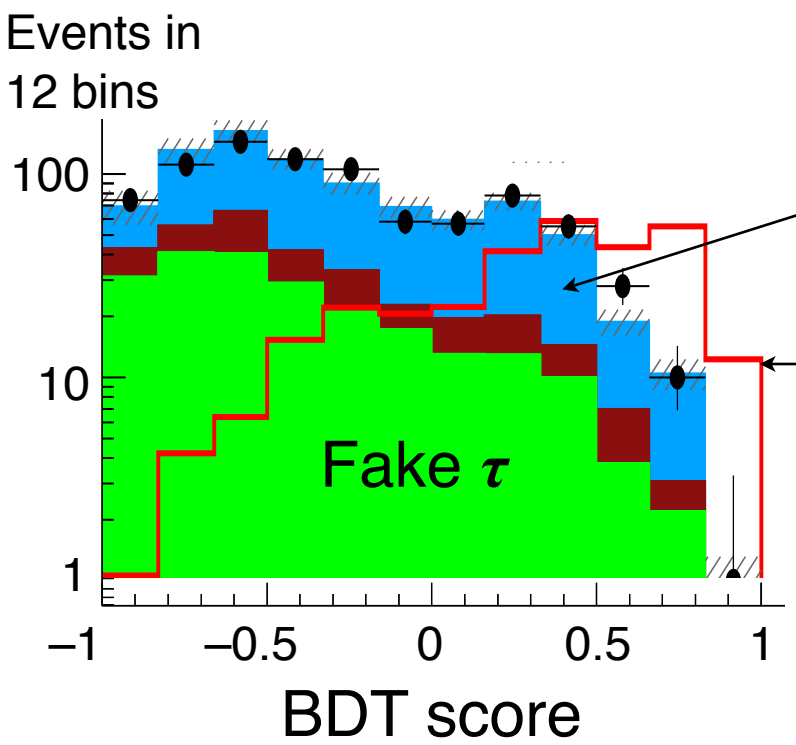
Method, validation of $Z \to \tau\tau$

Hong

- Fact: $pp \to Z$ same for $Z \to \tau\tau$, $Z \to \mu\mu$
- Select $Z \to \mu\mu$ with $M_{\mu\mu} > 40$, loosely isolated μ
- Use MC to decay τ in μ's place

$Z \to \tau\tau$ *control region*
$H \to \tau\tau \to \ell h$, $\geq 2j$
ATLAS Prelim., 8 TeV [c]

Control region definition
$M_{T,W} < 40$ to veto $W \to \ell\nu$
$M(\tau\tau) < 110$ to veto $H \to \tau\tau$



$Z \to \tau\tau$ good modeling in BDT

$H \to \tau\tau$ x50

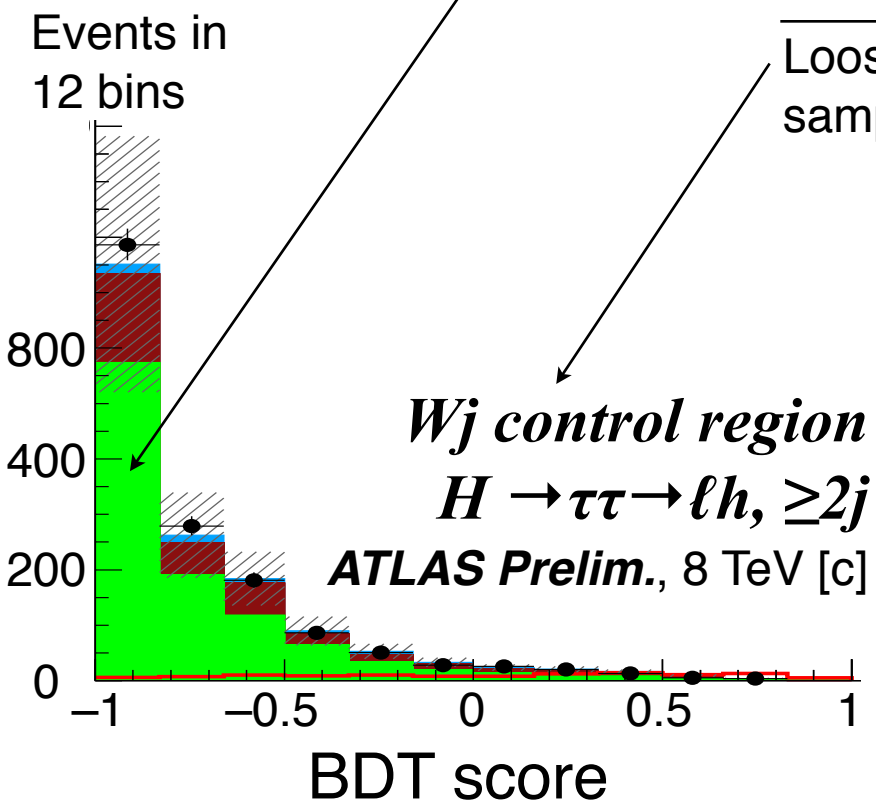
Method, validation of jet faking τ

- $Wjet \rightarrow \ell h_{\text{fake}}$ fakes $H \rightarrow \tau\tau \rightarrow \ell h$
- N_{fail} are signal-like events with h failing strict id.
- Get fail-to-pass ratio using a pure jet sample

$$\text{Fake } \tau = N_{\text{fail}} \cdot \left(\frac{N_{\text{pass}}}{N_{\text{fail}}} \right)$$

Loose sample

Wj sample: $M_{T,W} > 70$
jj sample: failed ℓ iso.



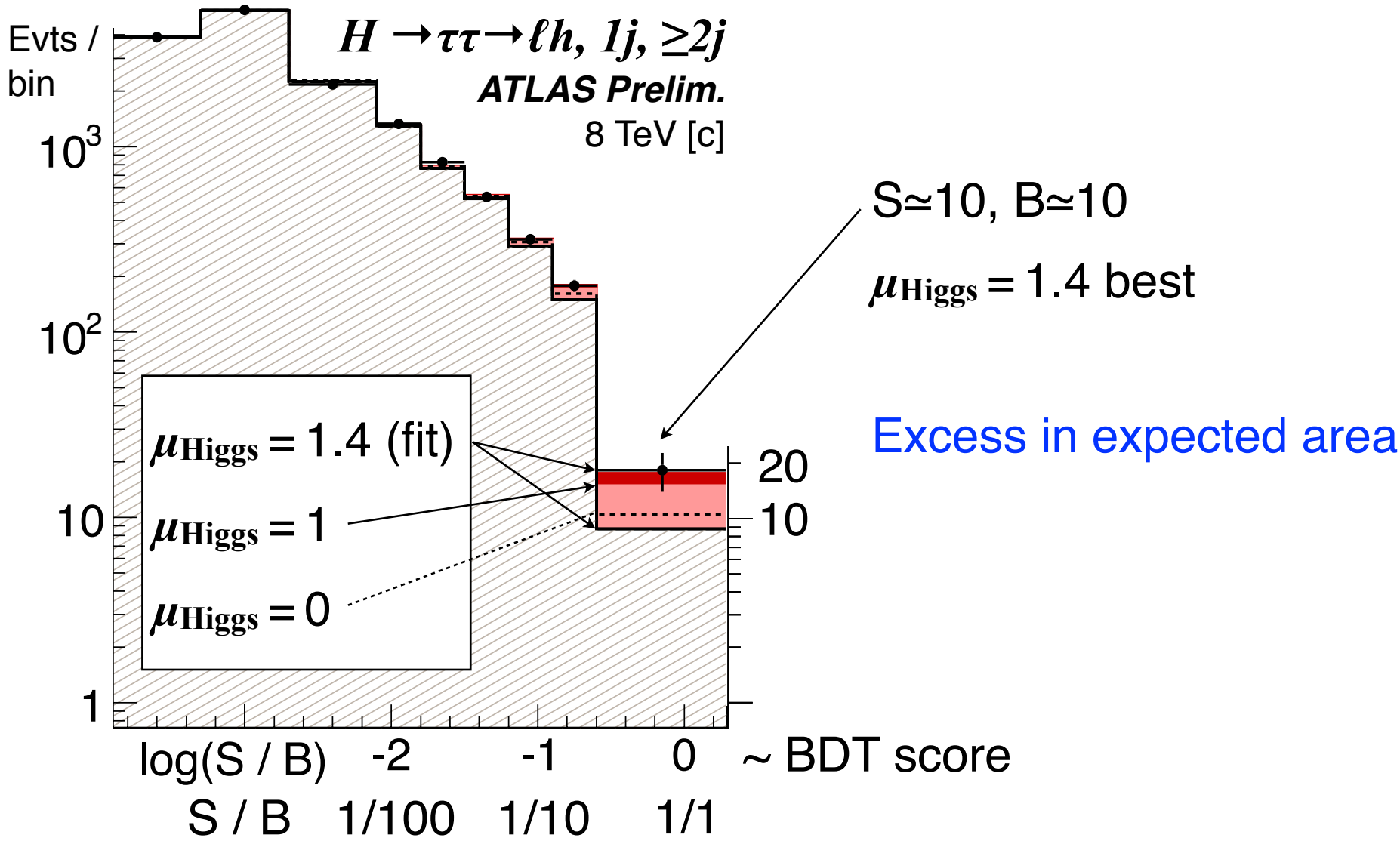
Good modeling in BDT

Pre-sel.
Analysis
Results

BDT applied to data

Hong

- Look at classification for ℓh in for $1j, \geq 2j$

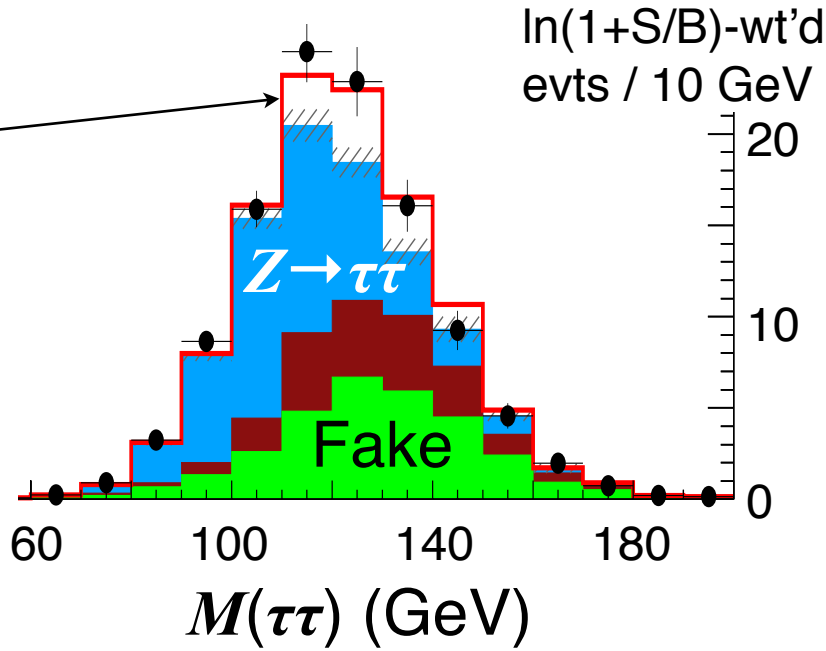


Combined result v. 125

$H \to \tau\tau \to \ell h$, $\geq 2j$
ATLAS Prelim., 8 TeV [c]

- S/B weighted $M(\tau\tau)$ for $1j$, $\geq 2j$

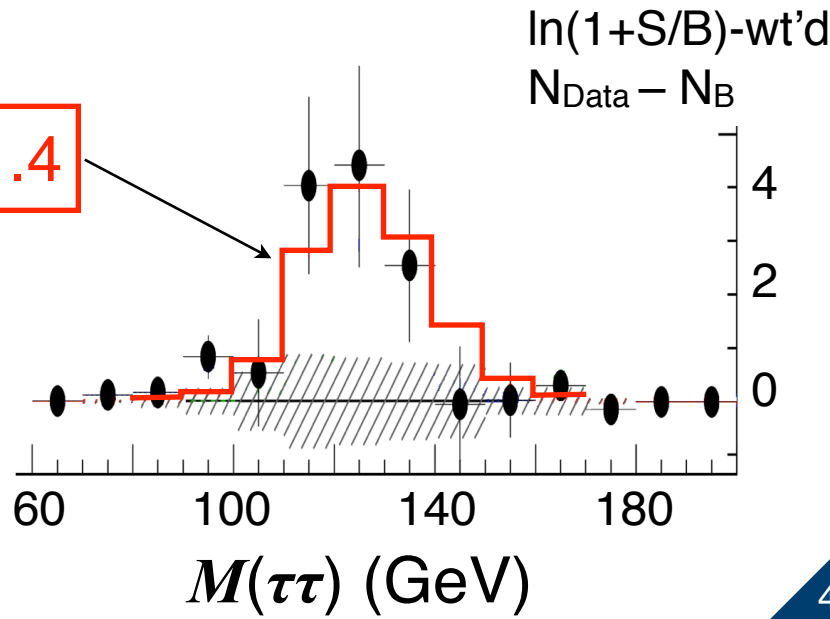
$H \to \tau\tau$
(μ=1.4)



- Significance (with $\ell\ell$, hh) is 4.1σ, 3.2σ
  observed expected

- Excess at expected for Higgs at 125

$\mu_{H125} = 1.4$

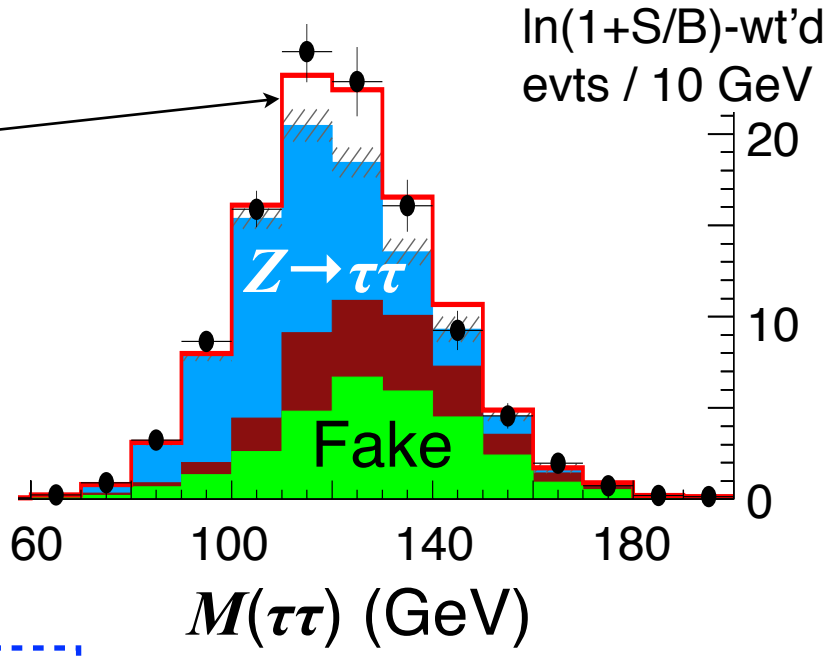


Combined result v. 125

- S/B weighted $M(\tau\tau)$ for *1j, ≥2j*

$H\to\tau\tau\to\ell h$, *≥2j*
ATLAS Prelim., 8 TeV [c]

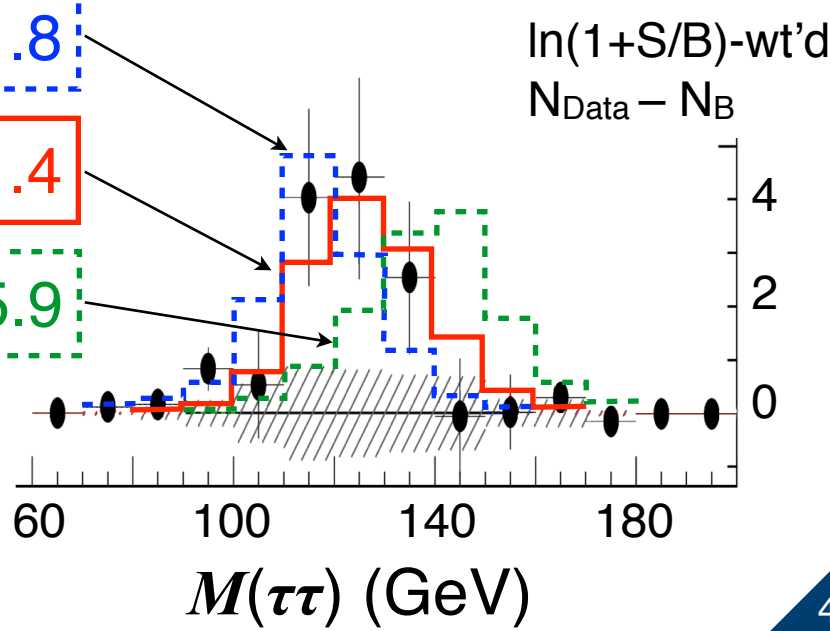
$H\to\tau\tau$
(μ=1.4)



- Significance (with $\ell\ell$, hh) is 4.1σ, 3.2σ
  observed expected

- Excess at expected for Higgs at 125

μ_{H110} = 1.8
μ_{H125} = 1.4
μ_{H150} = 5.9

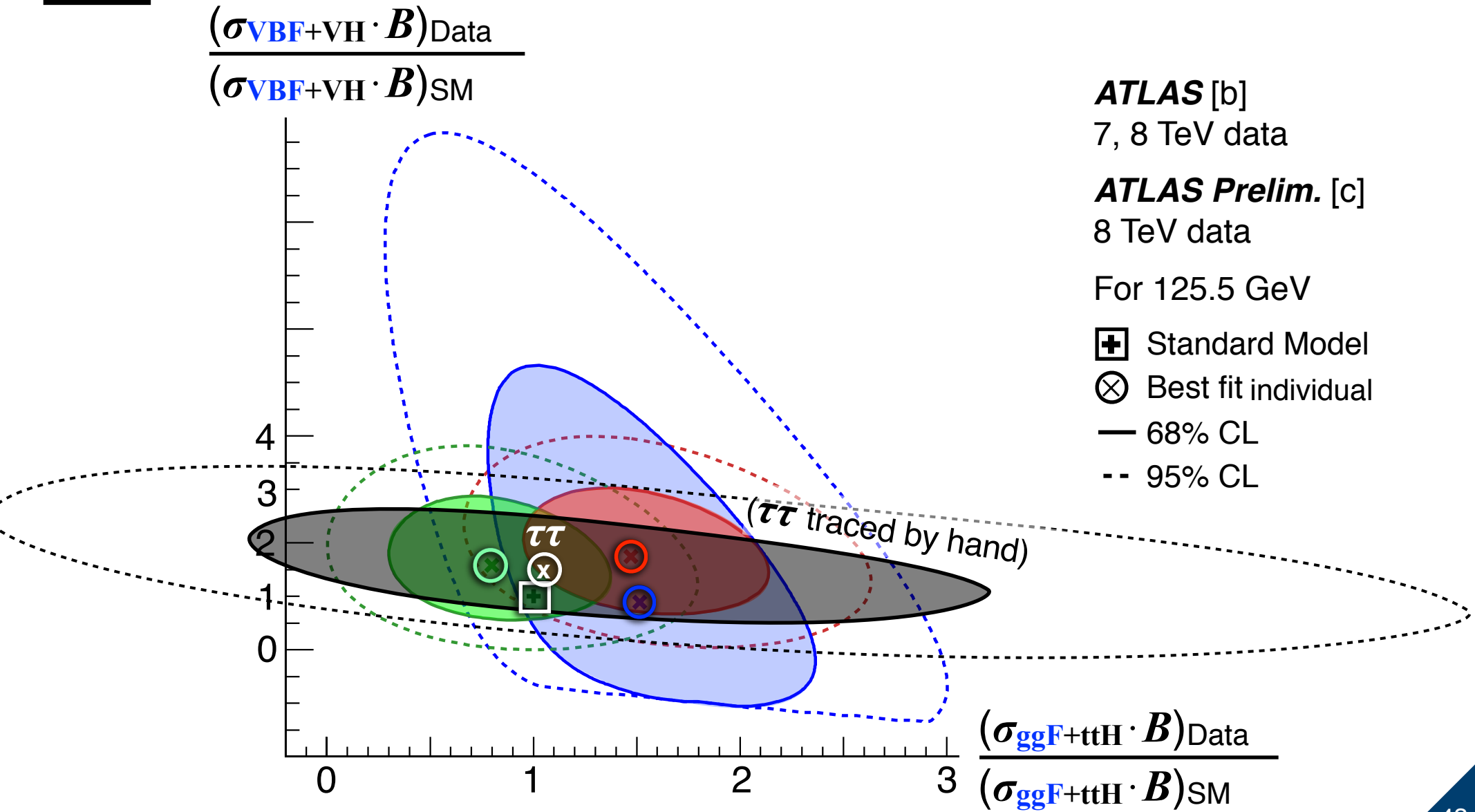


Pre-sel.
Analysis
Results

VBF v. ggF with $H \to \tau\tau$

Hong

- $\mu_{\text{Higgs}} = 1.6 \pm 0.6$ in ≥ 2 *jets* (mostly VBF)
  - 30% stat.
  - 30% syst.

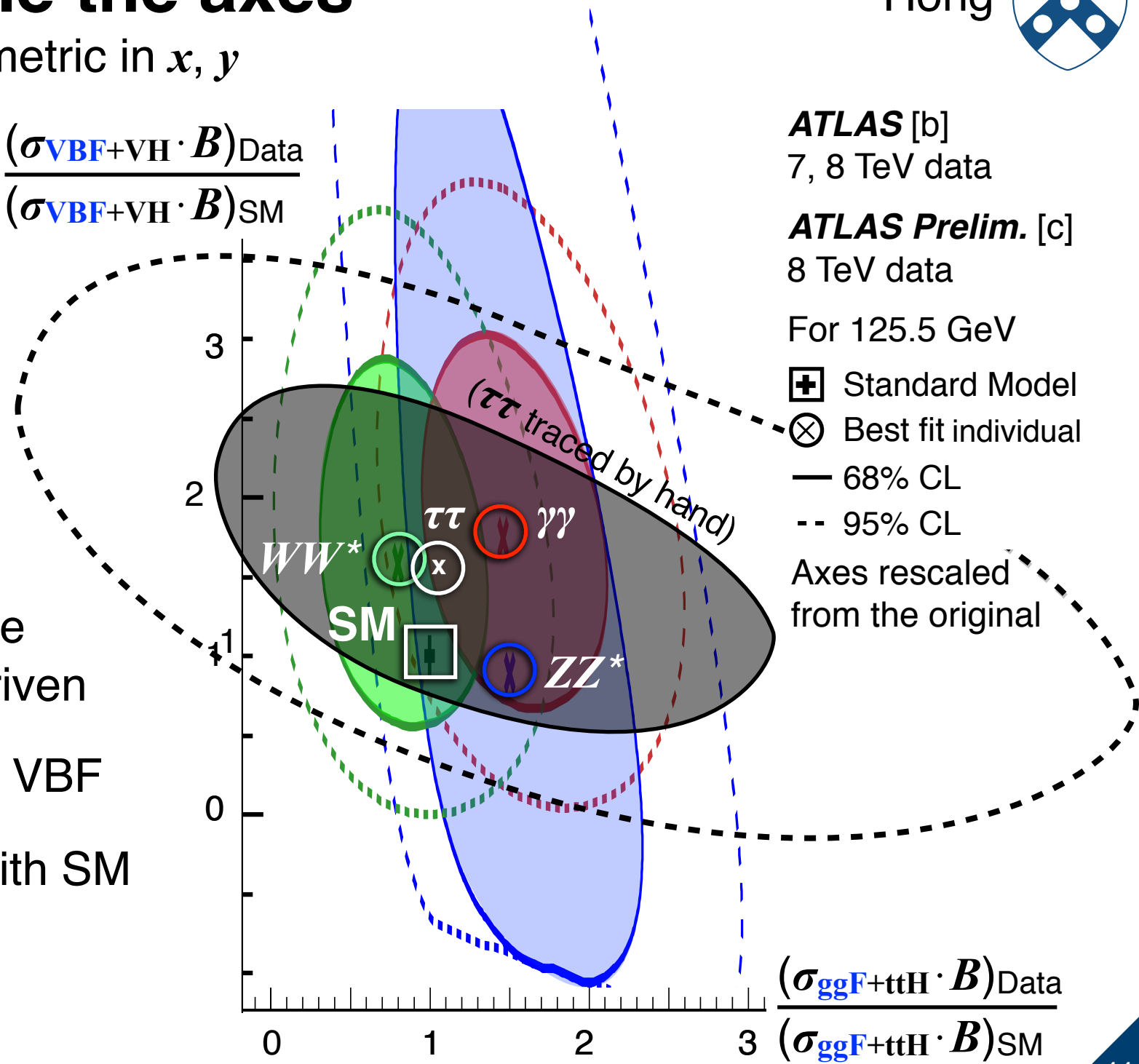


Pre-sel.
Analysis
Results

Rescale the axes

so same metric in x, y

Hong



Observations

- $\tau\tau$ different shape because VBF-driven
- $\tau\tau \sim WW^* \sim \gamma\gamma$ in VBF
- All consistent with SM within errors

Outline

Introduction

- Higgs via VBF
- ATLAS at LHC

Focus on similar final states

- VBF $H \rightarrow WW^* \rightarrow e\,\mu \quad \nu_e\,\nu_\mu$
- VBF $H \rightarrow \tau\tau \rightarrow \ell\,h \quad \nu_\ell\,\nu_\tau\,\nu_\tau$

Missing E_T (MET)

2 lepton-like objects

→ Putting it together

Putting it together into *g*

Hong

Are Higgs couplings modified?

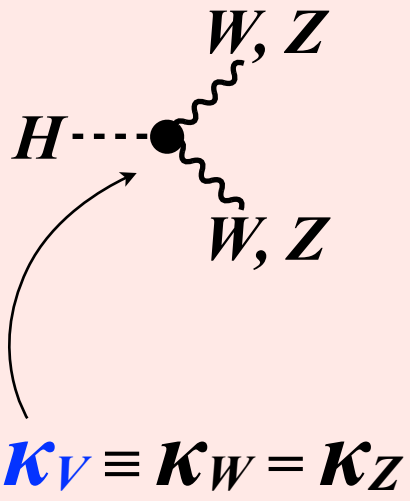
- Consider ratio w.r.t. SM

$$\kappa_X \equiv \frac{g_{X,\,\mathrm{Data}}}{g_{X,\,\mathrm{SM}}} = 1 \text{ for SM value}$$

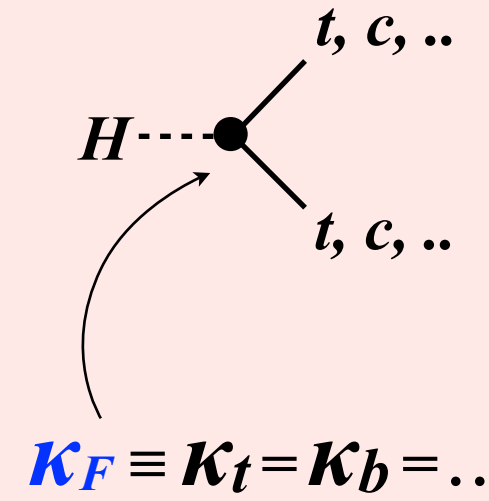
for any particle "*X*"

If we had large statistics, determine κ for each vertex

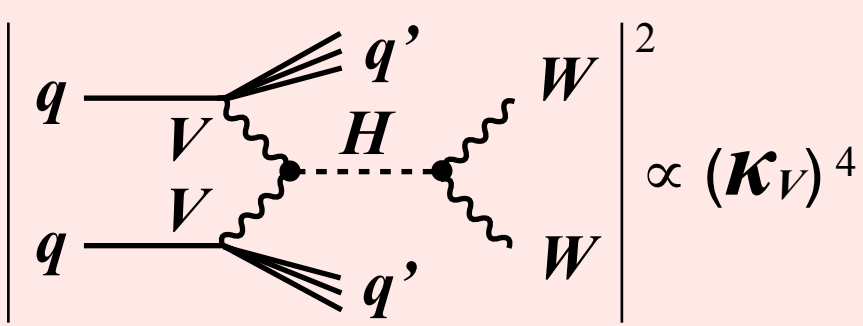
- But we don't (yet)
- Usually "lump" some together to taste, e.g., $\kappa_V \equiv \kappa_W = \kappa_Z$



Vector bosons



Fermions



Example

Higgs in EW same as in fermion?

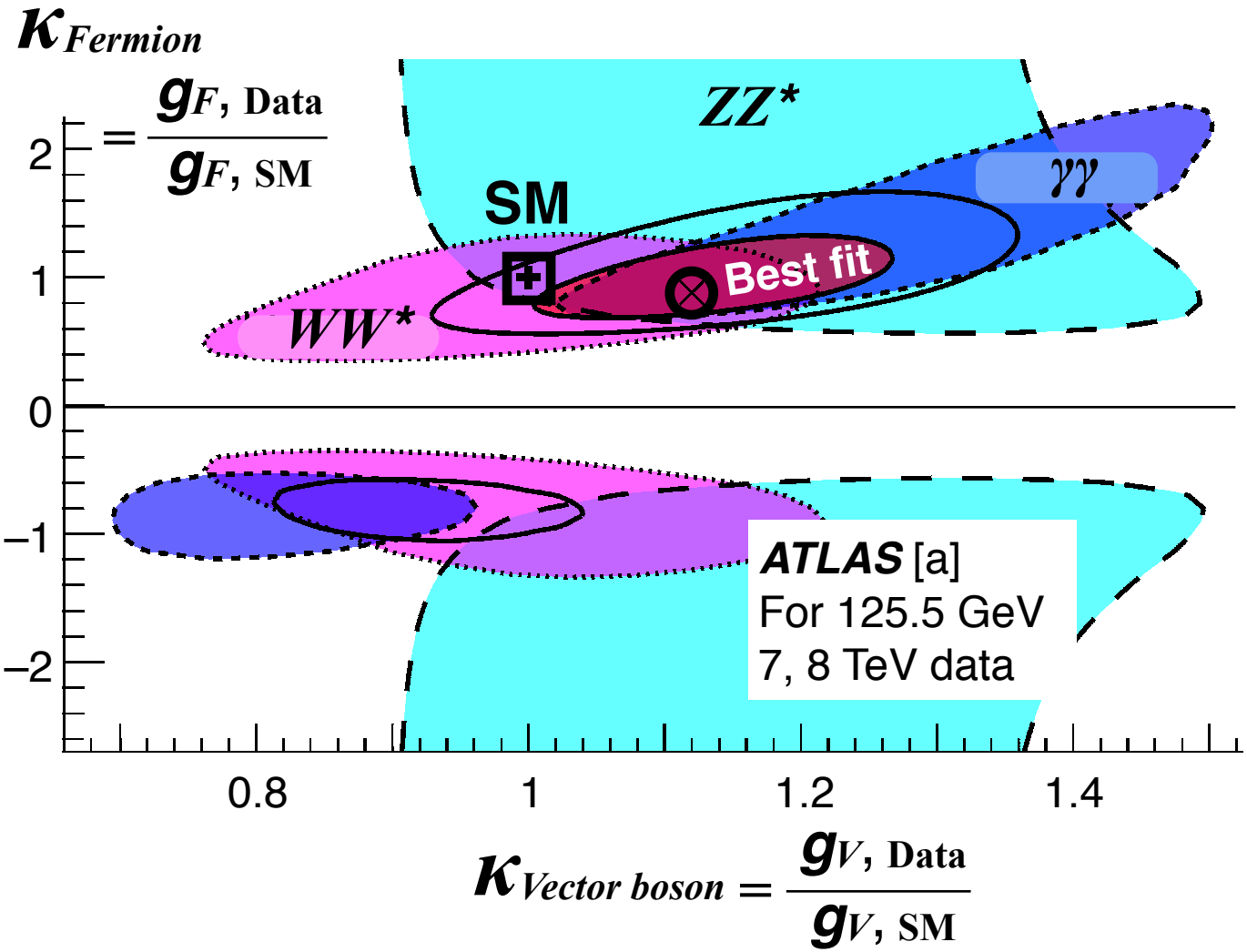
Hong

Benchmark scenario:

- Vector boson couplings deviate from SM by common factor κ_{Vector}
- Fermions deviate from SM by common factor $\kappa_{Fermion}$

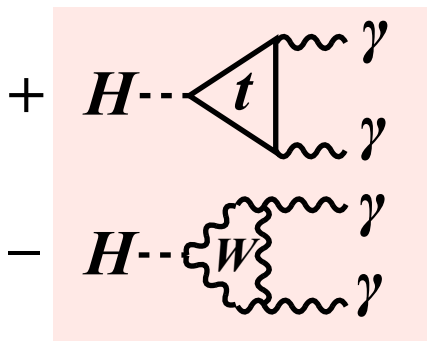
Results

- Consistent with SM, but large errors



Features

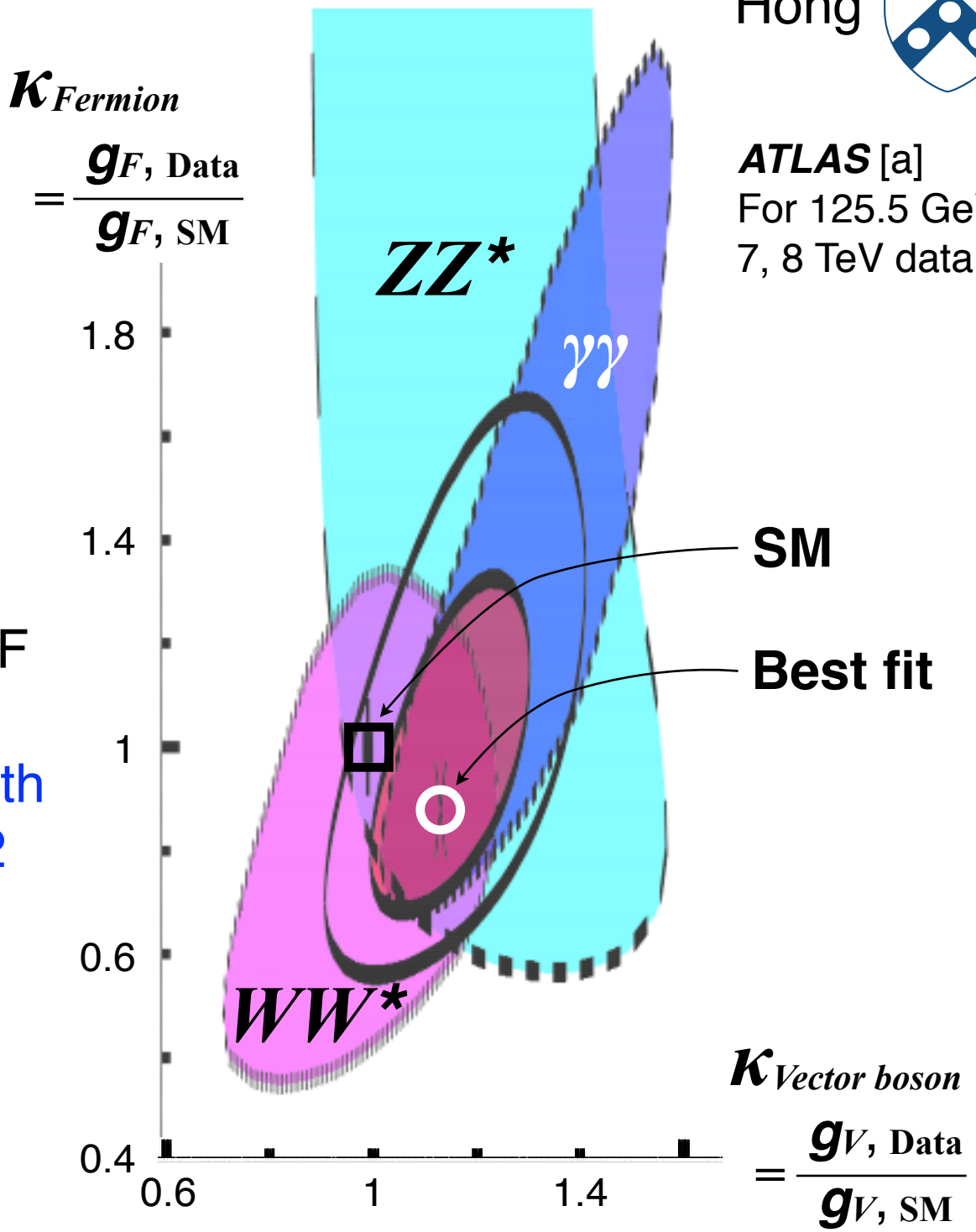
- All rates $\propto \kappa^2$, except for $\gamma\gamma$



Rescale the axes

and omit negative solution

Hong



ATLAS [a]
For 125.5 GeV
7, 8 TeV data

Observations

- All far from (0, 0)
- See κ_V 2x better than κ_F,
  ggF rate 2x better than VBF

VBF is statistics limited, so both axes will get better with Run-2

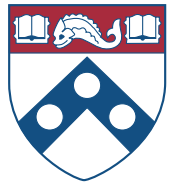
What if rates remain high?

Hong

Higgs width or something else? Take WW^* as example.

Rate depends on width: WW^* rate $= (\sigma \cdot B)_{WW} \equiv \sigma \cdot \dfrac{\Gamma_{WW}}{\Gamma_{\text{total width}}}$

What if rates remain high?



Higgs width or something else? Take WW^* as example.

Rate depends on width: WW^* rate $= (\sigma \cdot B)_{WW} \equiv \sigma \cdot \dfrac{\Gamma_{WW}}{\Gamma_{\text{total width}}}$

Measure VBF rate: $\mu_{W,\text{VBF}} \equiv \dfrac{(\sigma \cdot B)_{WW,\text{VBF,Data}}}{(\sigma \cdot B)_{WW,\text{VBF,SM}}} = \dfrac{(\kappa_V)^2 (\kappa_W)^2}{(\kappa_{\text{total}})^2}$

Measure ggF rate: $\mu_{W,\text{ggF}} \equiv \dfrac{(\sigma \cdot B)_{WW,\text{ ggF, Data}}}{(\sigma \cdot B)_{WW,\text{ ggF, SM}}} = \dfrac{(\kappa_g)^2 (\kappa_W)^2}{(\kappa_{\text{total}})^2}$

What if rates remain high?

Hong

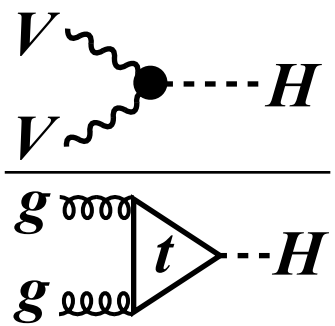
Higgs width or something else? Take WW^* as example.

Rate depends on width: WW^* rate $= (\sigma \cdot B)_{WW} \equiv \sigma \cdot \dfrac{\Gamma_{WW}}{\Gamma_{\text{total width}}}$

Measure VBF rate: $\mu_{W,\text{VBF}} \equiv \dfrac{(\sigma \cdot B)_{WW,\text{VBF,Data}}}{(\sigma \cdot B)_{WW,\text{VBF,SM}}} = \dfrac{(\kappa_V)^2 (\kappa_W)^2}{(\kappa_{\text{total}})^2}$

Measure ggF rate: $\mu_{W,\text{ggF}} \equiv \dfrac{(\sigma \cdot B)_{WW,\text{ ggF, Data}}}{(\sigma \cdot B)_{WW,\text{ ggF, SM}}} = \dfrac{(\kappa_g)^2 (\kappa_W)^2}{(\kappa_{\text{total}})^2}$

Take ratio of rates: $R_W = \dfrac{\mu_{W,\text{VBF}}}{\mu_{W,\text{ ggF}}} = \dfrac{(\kappa_V)^2}{(\kappa_g)^2} \sim$



- No κ_{total}
- No WW^*

What if rates remain high?

Hong

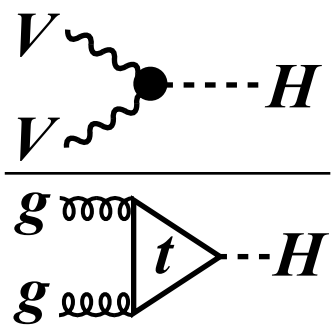
Higgs width or something else? Take WW^* as example.

Rate depends on width: WW^* rate $= (\sigma \cdot B)_{WW} \equiv \sigma \cdot \dfrac{\Gamma_{WW}}{\Gamma_{\text{total width}}}$

Measure VBF rate: $\mu_{W,\text{VBF}} \equiv \dfrac{(\sigma \cdot B)_{WW,\text{VBF,Data}}}{(\sigma \cdot B)_{WW,\text{VBF,SM}}} = \dfrac{(\kappa_V)^2 (\kappa_W)^2}{(\kappa_{\text{total}})^2}$

Measure ggF rate: $\mu_{W,\text{ggF}} \equiv \dfrac{(\sigma \cdot B)_{WW,\text{ ggF, Data}}}{(\sigma \cdot B)_{WW,\text{ ggF, SM}}} = \dfrac{(\kappa_g)^2 (\kappa_W)^2}{(\kappa_{\text{total}})^2}$

Take ratio of rates: $R_W = \dfrac{\mu_{W,\text{VBF}}}{\mu_{W,\text{ ggF}}} = \dfrac{(\kappa_V)^2}{(\kappa_g)^2} \sim$



- No κ_{total}
- No WW^*

$R \neq 1$ means κ_V or κ_g not SM.

Conclusions

Gave details on VBF $H \rightarrow WW^*$, VBF $H \rightarrow \tau\tau$

- Evidence of VBF Higgs
- Evidence of Higgs-lepton coupling

LHC as a vector boson collider

- VBF is statistically limited, so Run-2 data crucial
- VBF is important tool to study Higgs sector

Great potential for sensitivity to new physics!

Thanks

This talk has been heavily influenced from inputs from many.
In particular, I'd like to acknowledge

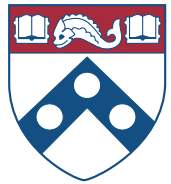
• J. Alison	Chicago
• K. Black	Boston
• B. Cerio	Duke
• M. Morii	Harvard
• P. Chang	Illinois
• I. J. Kroll	Penn
• E. Lipeles	Penn
• R. Ospanov	Penn
• A. Pranko	LBL
• D. Schaefer	Penn
• S. Sekula	Southern Methodist
• A. Tuna	Penn
• R. Vanguri	Penn

and many of my Penn & ATLAS co-workers who are not listed above.

Back-up material

ATLAS collaboration in *Nature*

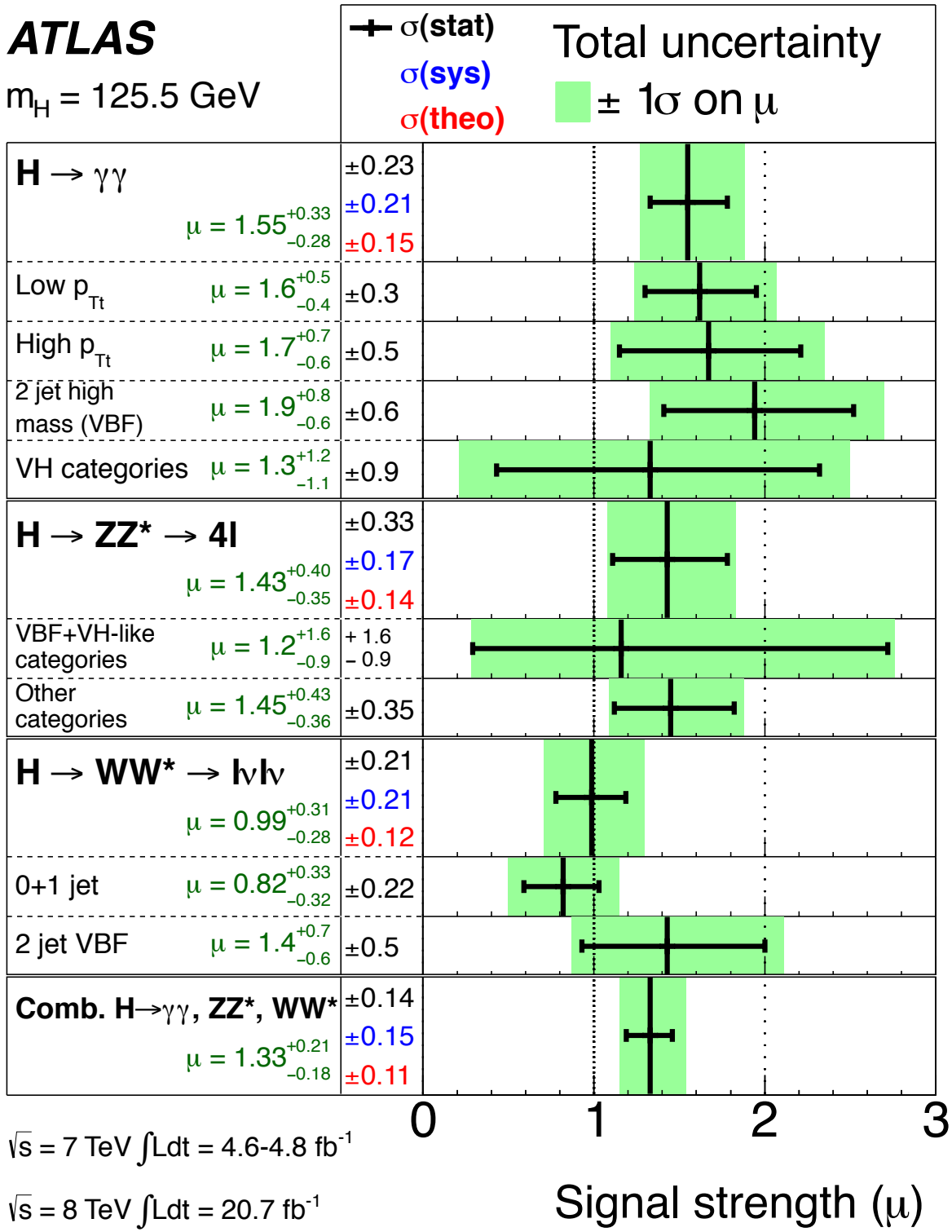
Hong



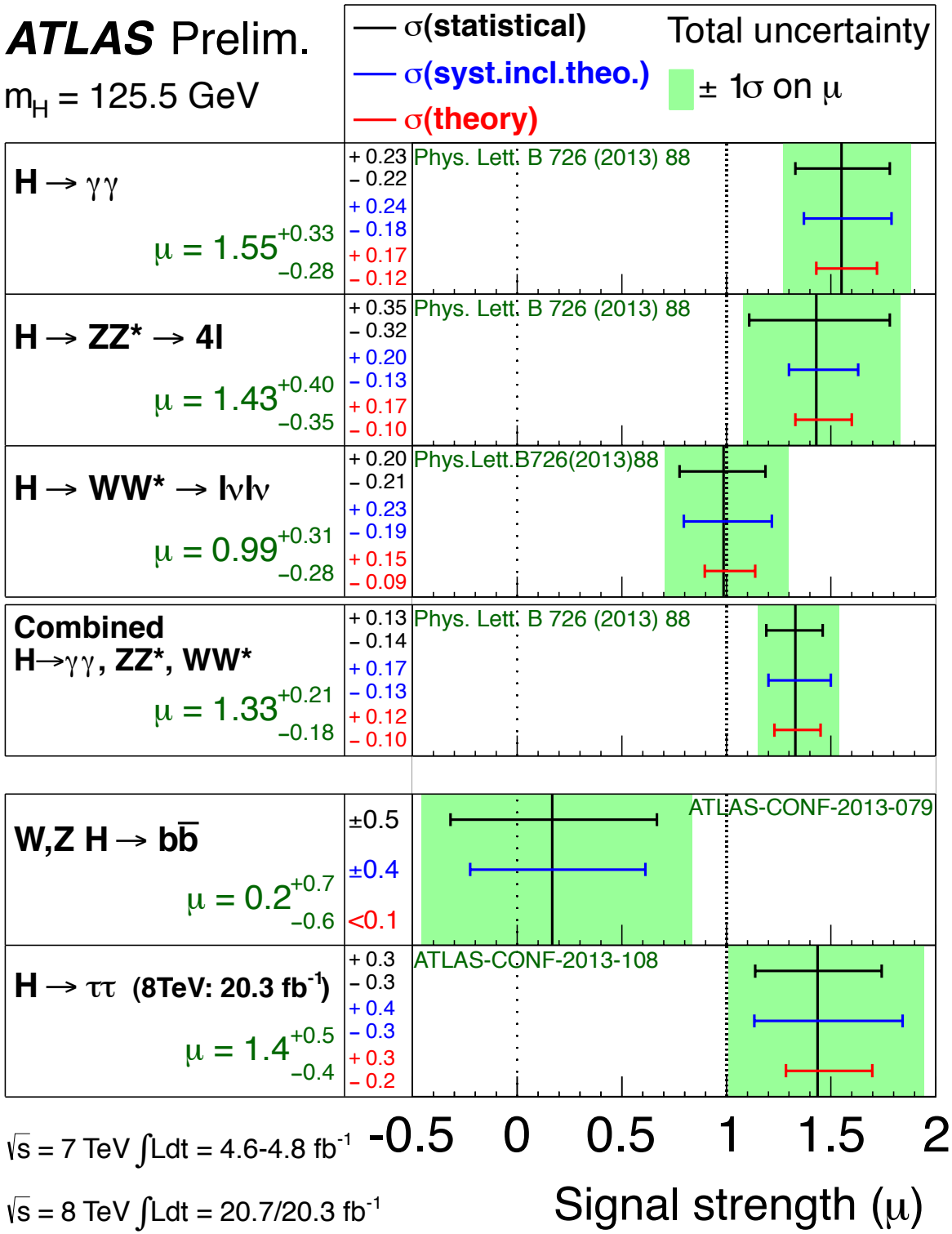
"Like a giant commune, [they] work, eat, and party together."

while discovering new physics!

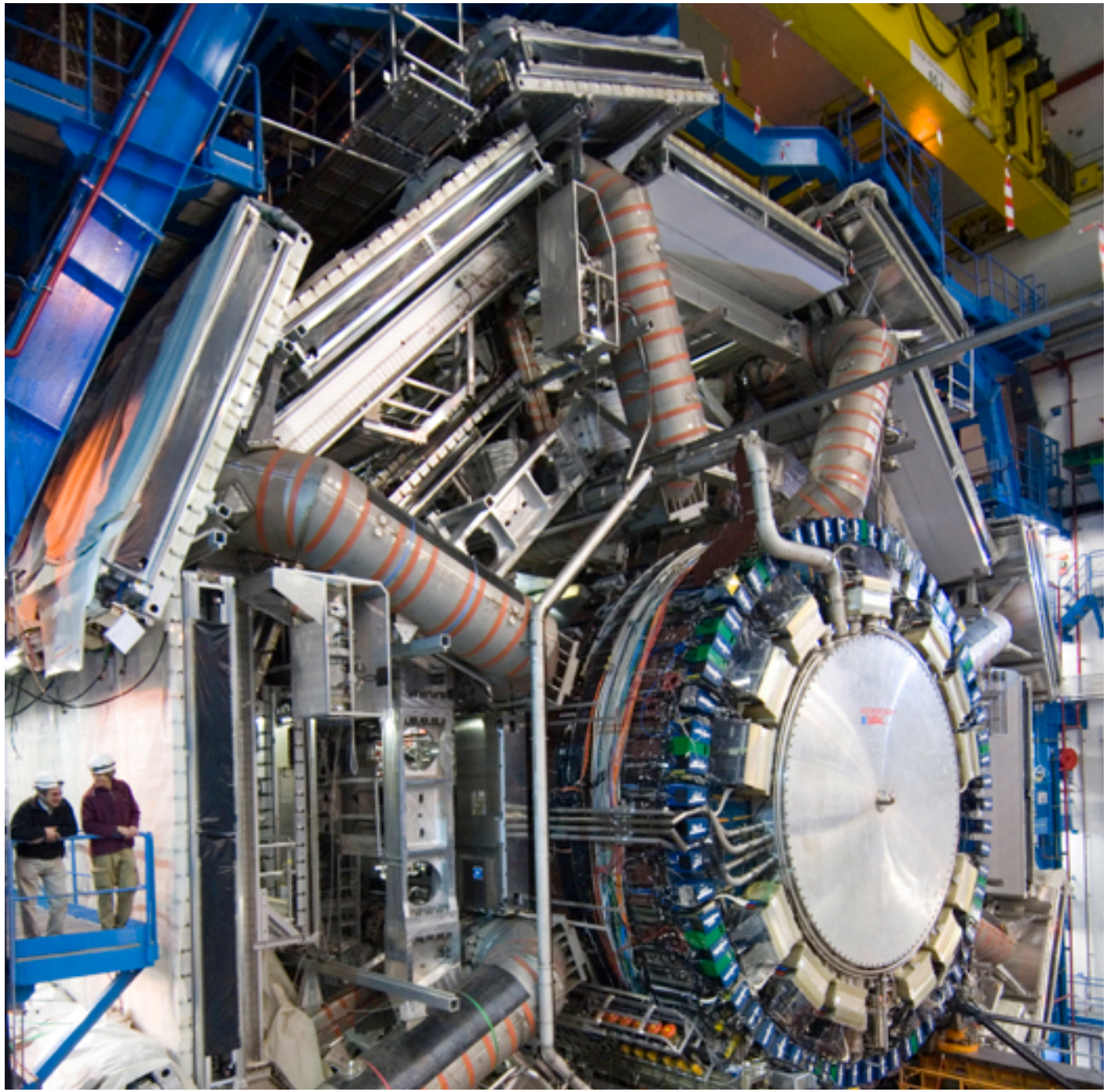
Same as p6

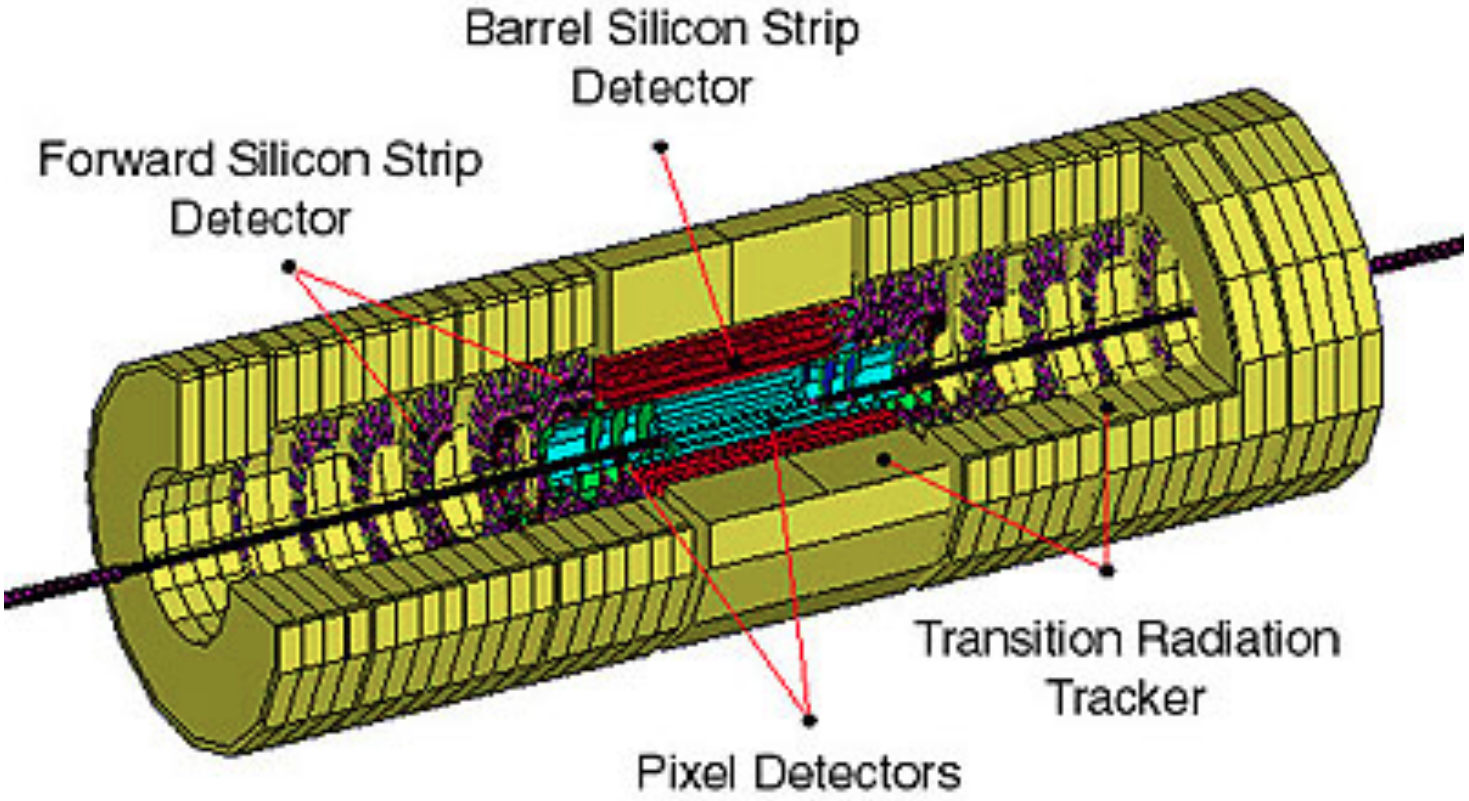

ATLAS
m_H = 125.5 GeV
σ(stat)
σ(sys)
σ(theo)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.55 +0.33 −0.28
±0.23
±0.21
±0.15
Low p_Tt
μ = 1.6 +0.5 −0.4
±0.3
High p_Tt
μ = 1.7 +0.7 −0.6
±0.5
2 jet high mass (VBF)
μ = 1.9 +0.8 −0.6
±0.6
VH categories
μ = 1.3 +1.2 −1.1
±0.9
H → ZZ* → 4l
μ = 1.43 +0.40 −0.35
±0.33
±0.17
±0.14
VBF+VH-like categories
μ = 1.2 +1.6 −0.9
+ 1.6
− 0.9
Other categories
μ = 1.45 +0.43 −0.36
±0.35
H → WW* → lνlν
μ = 0.99 +0.31 −0.28
±0.21
±0.21
±0.12
0+1 jet
μ = 0.82 +0.33 −0.32
±0.22
2 jet VBF
μ = 1.4 +0.7 −0.6
±0.5
Comb. H→γγ, ZZ*, WW*
μ = 1.33 +0.21 −0.18
±0.14
±0.15
±0.11
0
1
2
3
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
Signal strength (μ)

Similar to p6



ATLAS detector

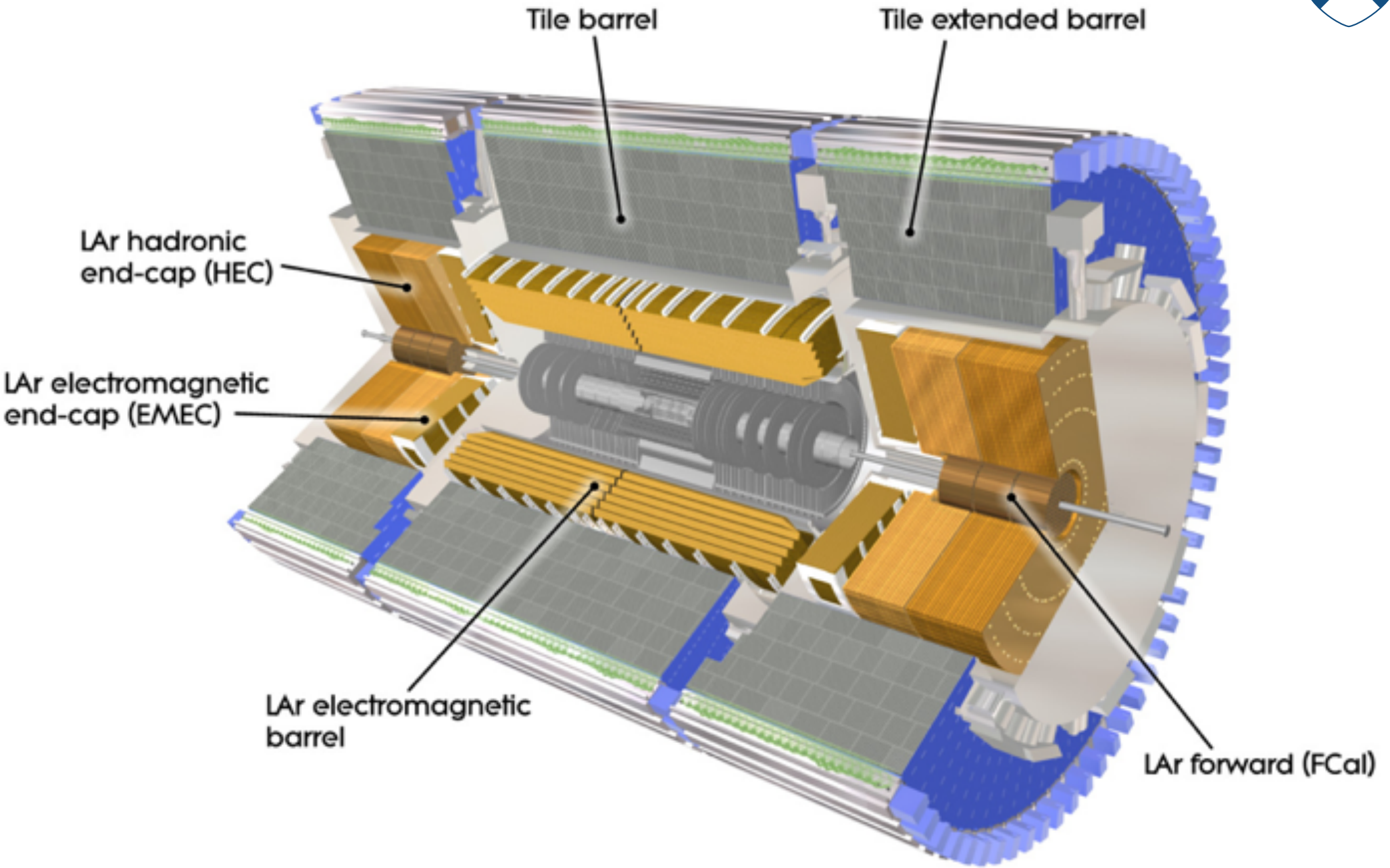




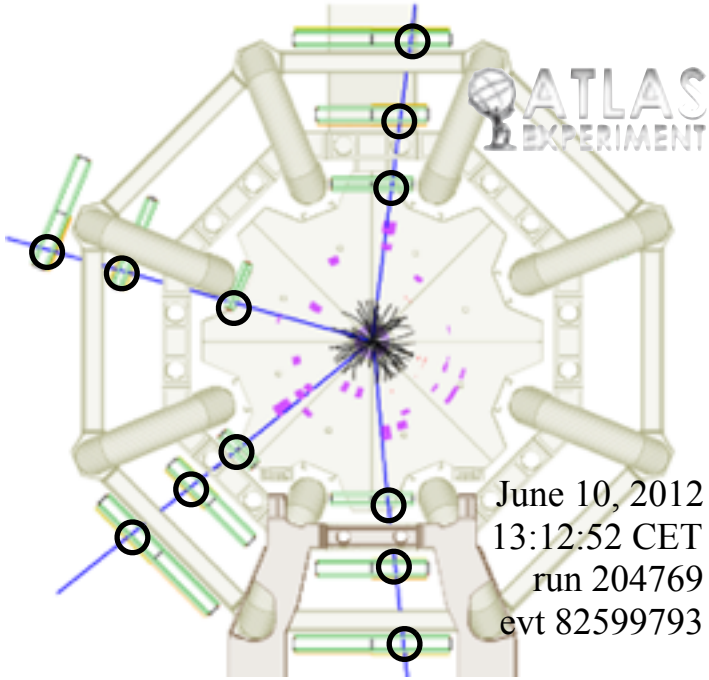
Inner Tracker

Inside the toroid

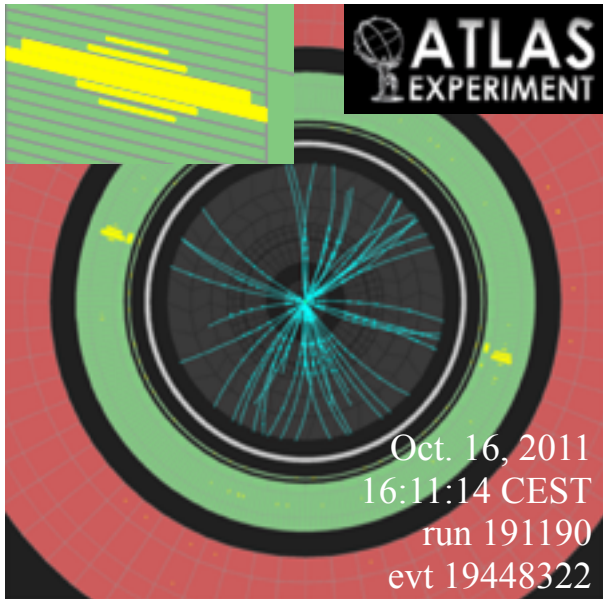
Hong



Muons, electrons



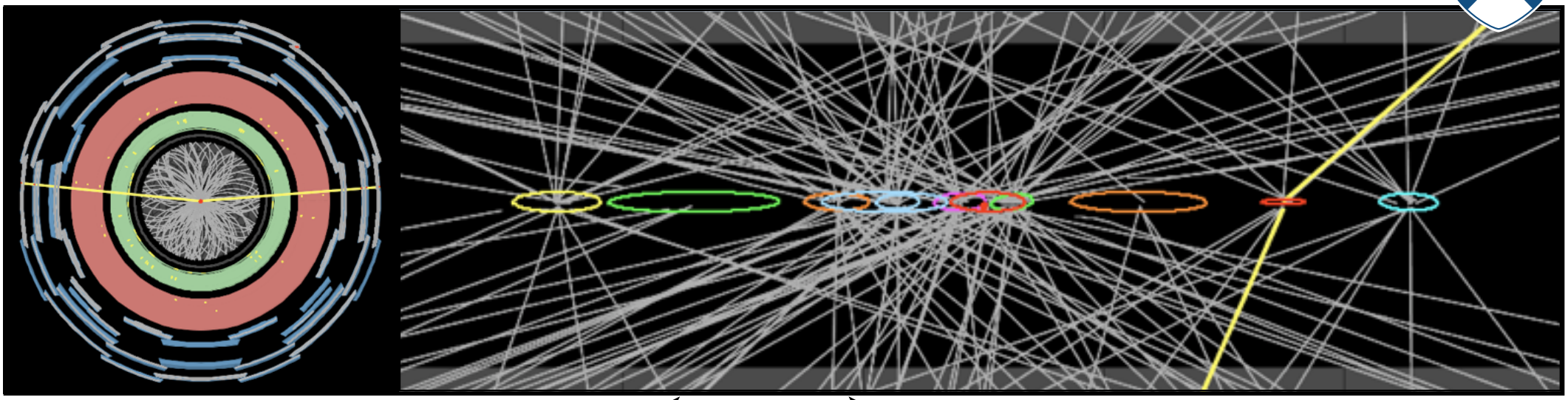
$H \rightarrow ZZ^* \rightarrow \mu\mu\mu\mu$



$H \rightarrow \gamma\gamma \rightarrow \gamma ee$

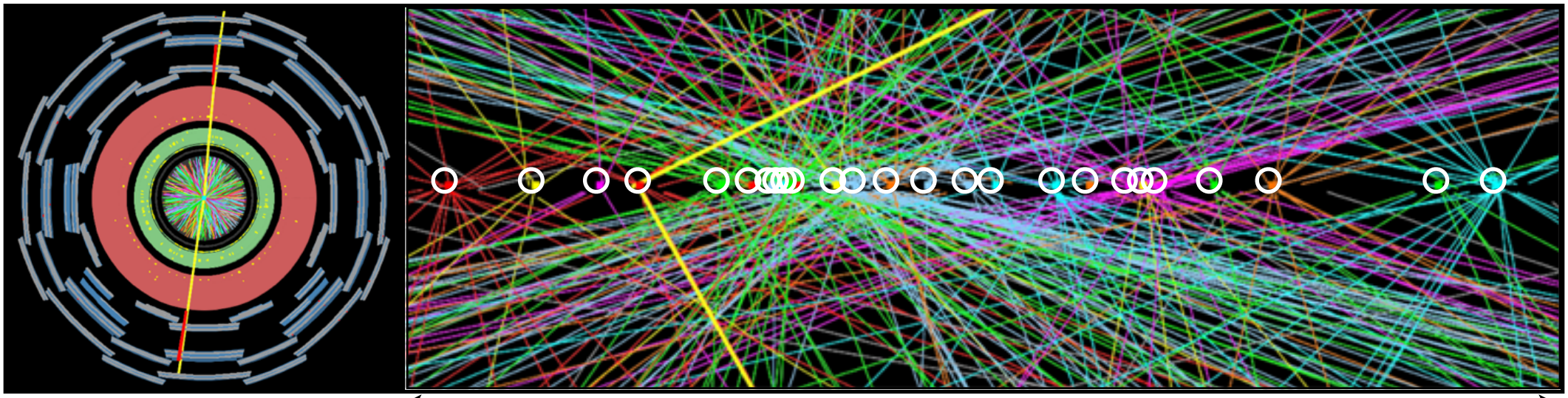
High luminosity → high pile-up ⟨μ⟩

Hong



2011, 11 vertices

Between vertices $\langle \Delta z \rangle \approx 2$ - 3 mm, $\sigma_{\Delta z} \approx 0.2$ mm



2012, 25 vertices

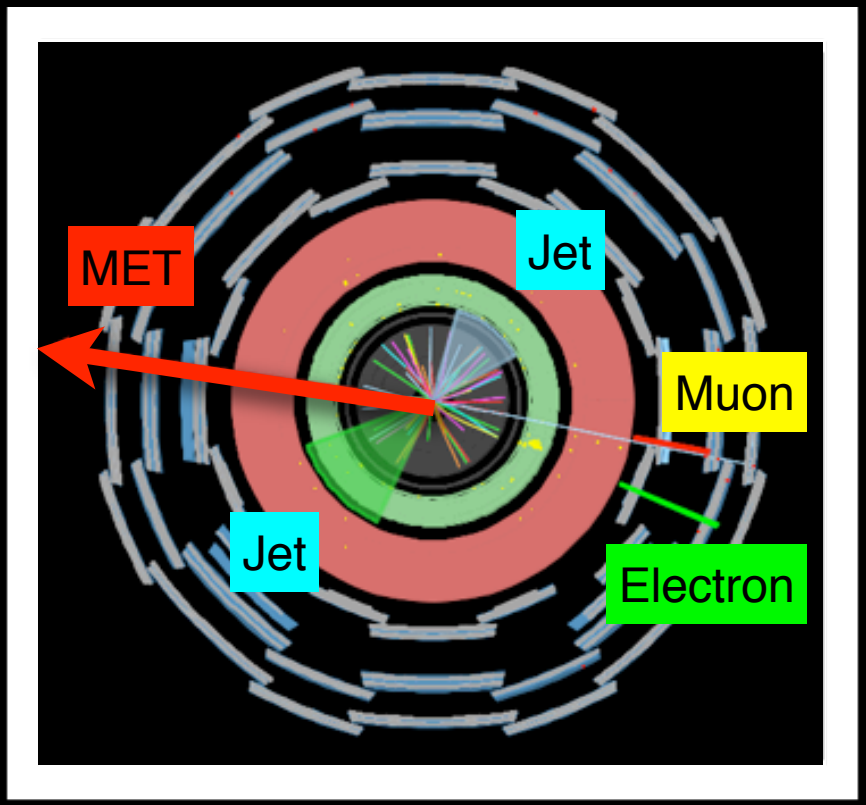
Interaction region width in $z \approx 5$ - 6 cm

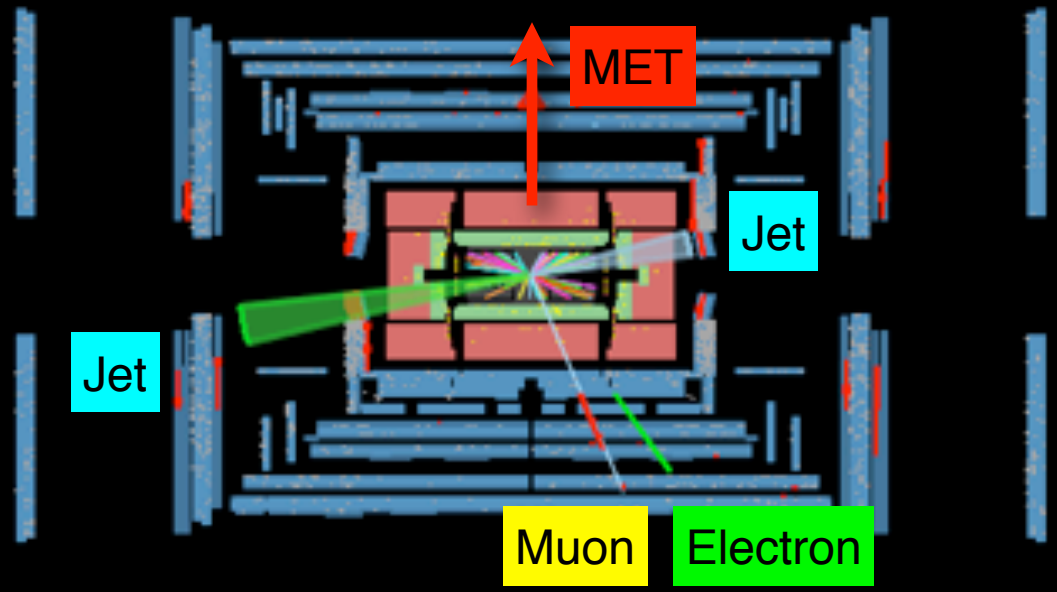
Pile-up increased from 2011 to 2012

VBF, $H\,jj \rightarrow WW^*\,jj \rightarrow e\mu\,jj\;MET$

Jun. 17, 2012
07:18:33 CEST
run 205071
evt 160243894

Hong





VBF ($\Delta\eta_{jj}$ = 4.7
M_{jj} = 531

HWW ($M_{e\mu}$ = 21 GeV
$\Delta\varphi_{\ell\ell}$ = 0.23
M_T = 134

Event characteristics

- Jets are forward with $\eta \sim \pm 2.4$
- Large $ttbar \rightarrow WbWb \rightarrow e\mu\ bb\ MET$
- Veto with *b*-tag operating pt. 85%

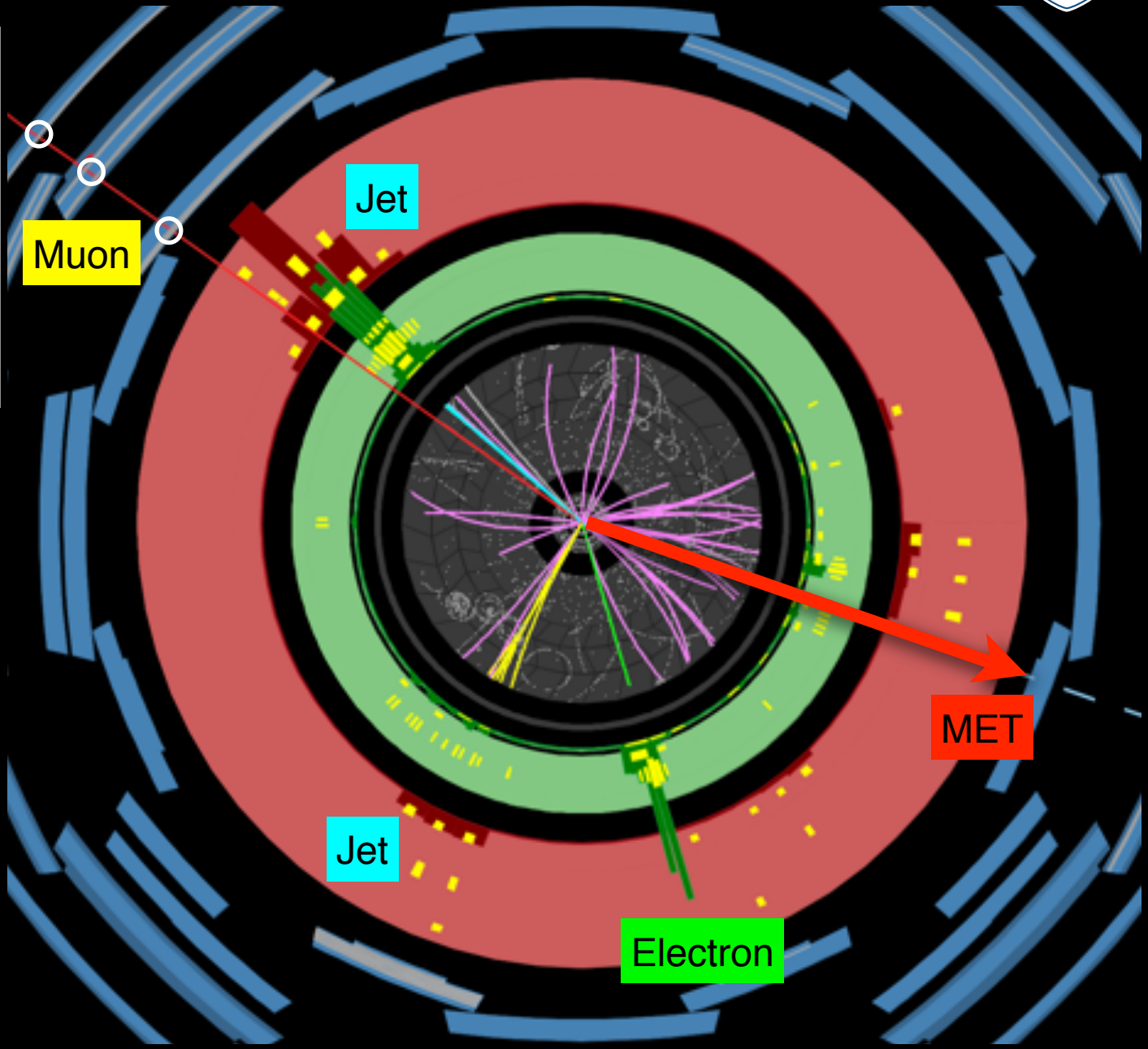
Another event that is VBF-like in *jj* & Higgs-like in decay

ttbar → WbWb → eμ bb MET

Hong

Right: Two *b*-tag jets, muon, electron, *MET*

Below: Zoom-in to see two displaced vertices for *b*-hadron decays

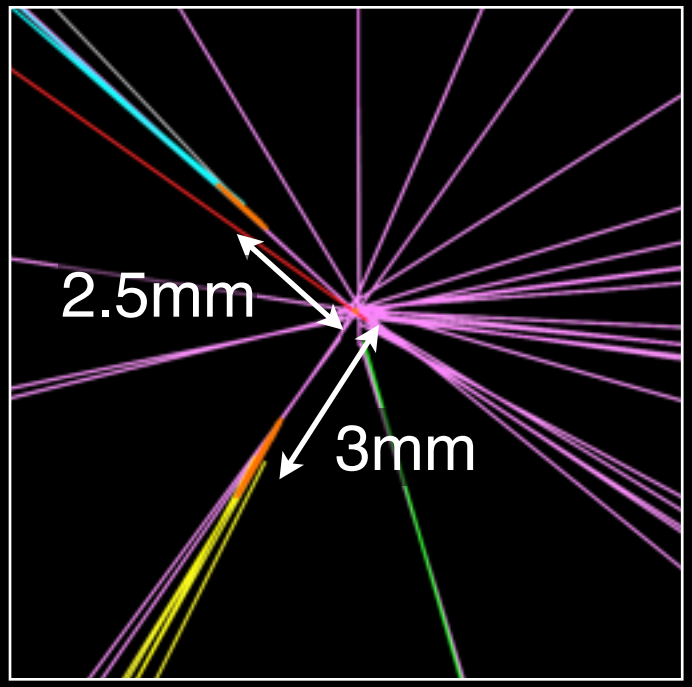


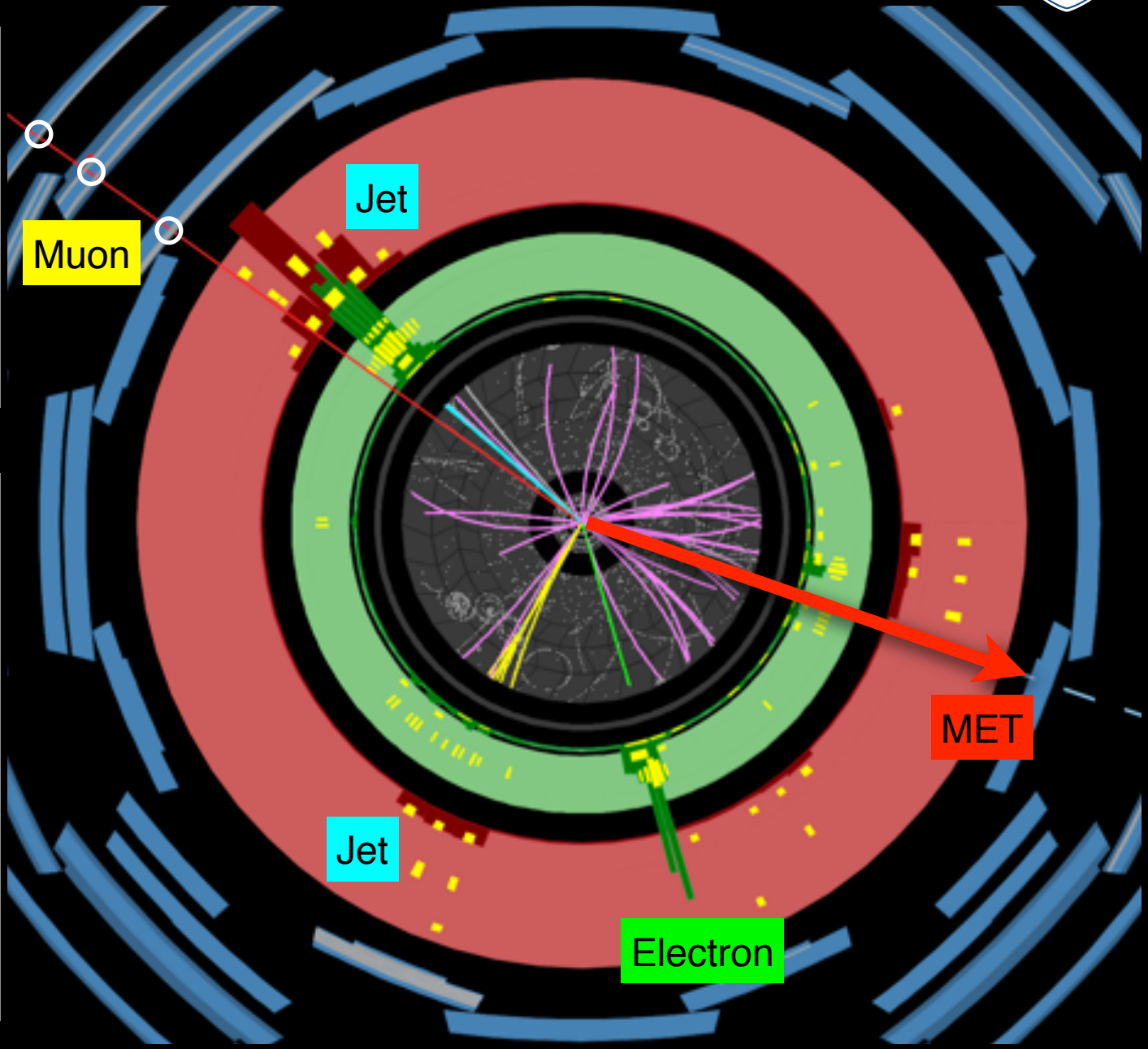
ttbar → *WbWb* → *eμ bb MET*

Hong

Right: Two *b*-tag jets, muon, electron, *MET*

Below: Zoom-in to see two displaced vertices for *b*-hadron decays

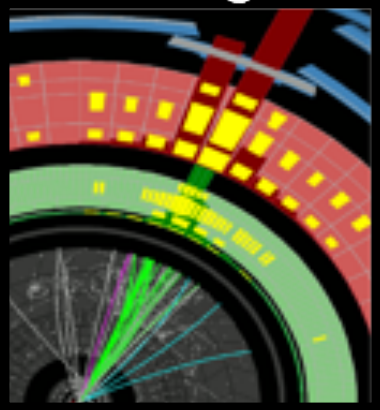


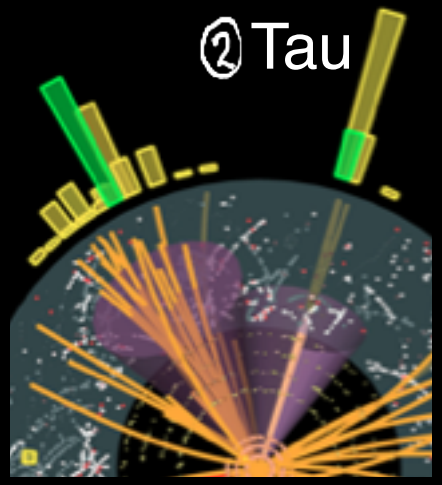


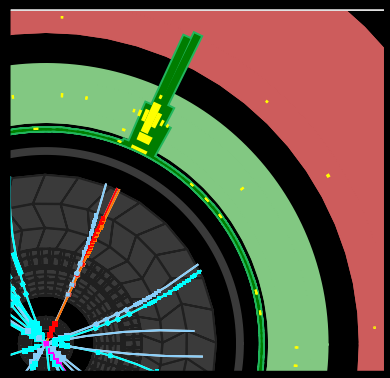
ttbar is a major background to VBF, *H* → *WW** → *ℓνℓν*

Comparison of

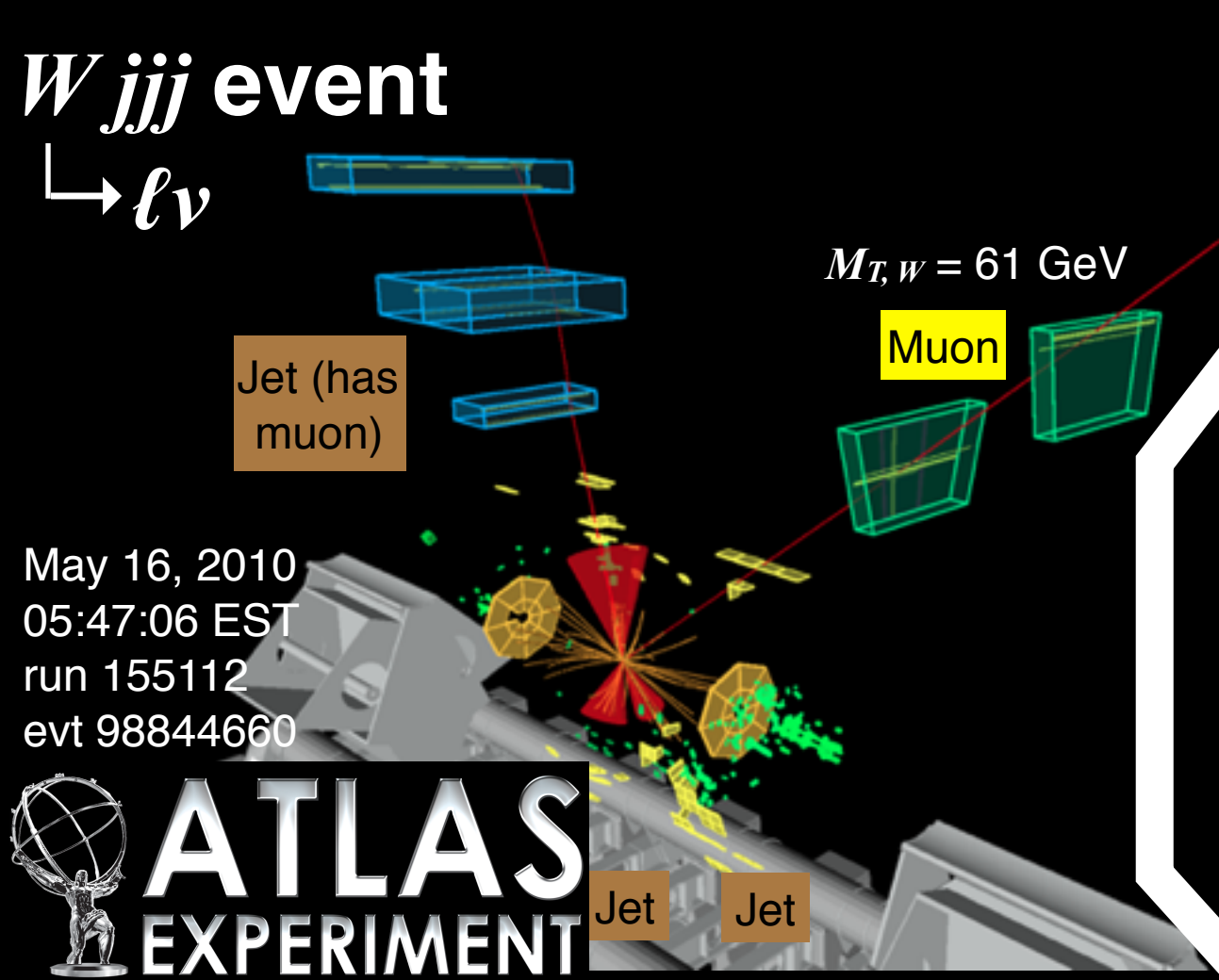
① Jet
② Tau (3-prong)
③ Electron

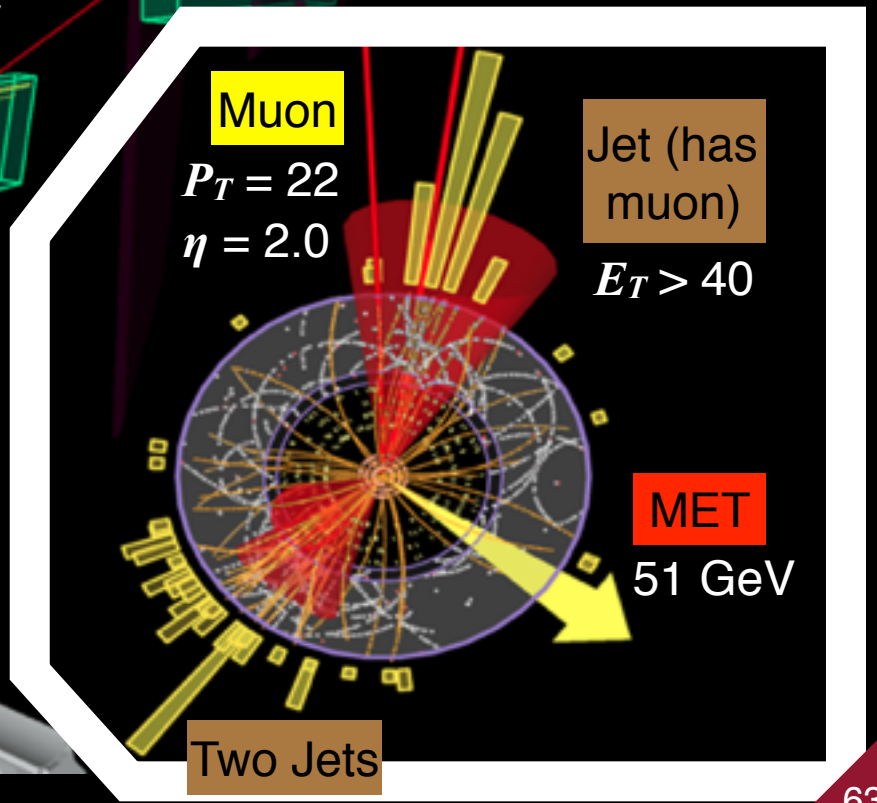






$W\,jjj$ event
$\hookrightarrow \ell\nu$

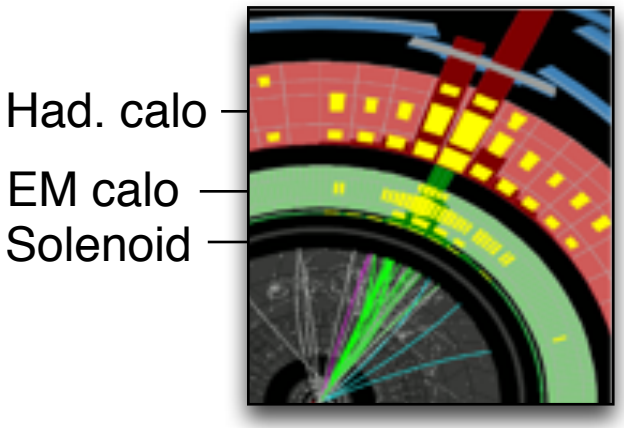


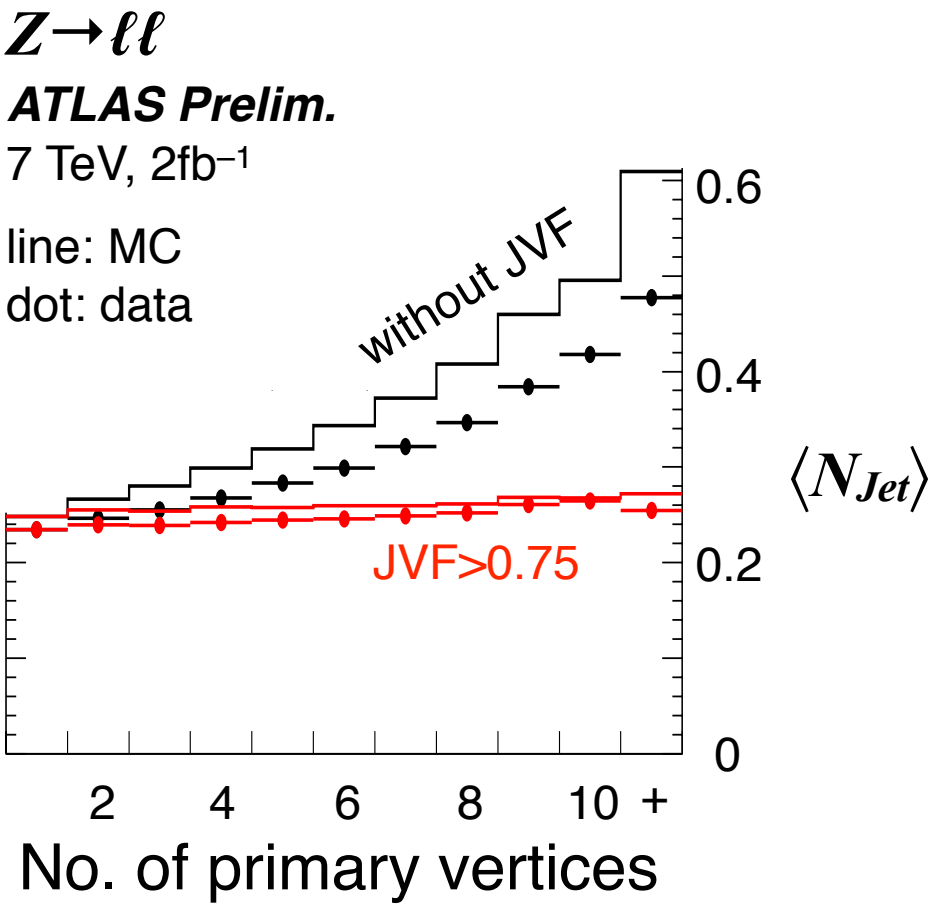


Jets

Calo clusters with anti-k_T, $R = 0.4$

Hong





Need two jets for VBF

- Jet Vtx. Fraction kills pile-up jets

Calibrate energy against γ, $Z \to \ell\ell$

- ~5% error on Jet Energy Scale

Jet energy scale

Hong

Define jet from clusters:

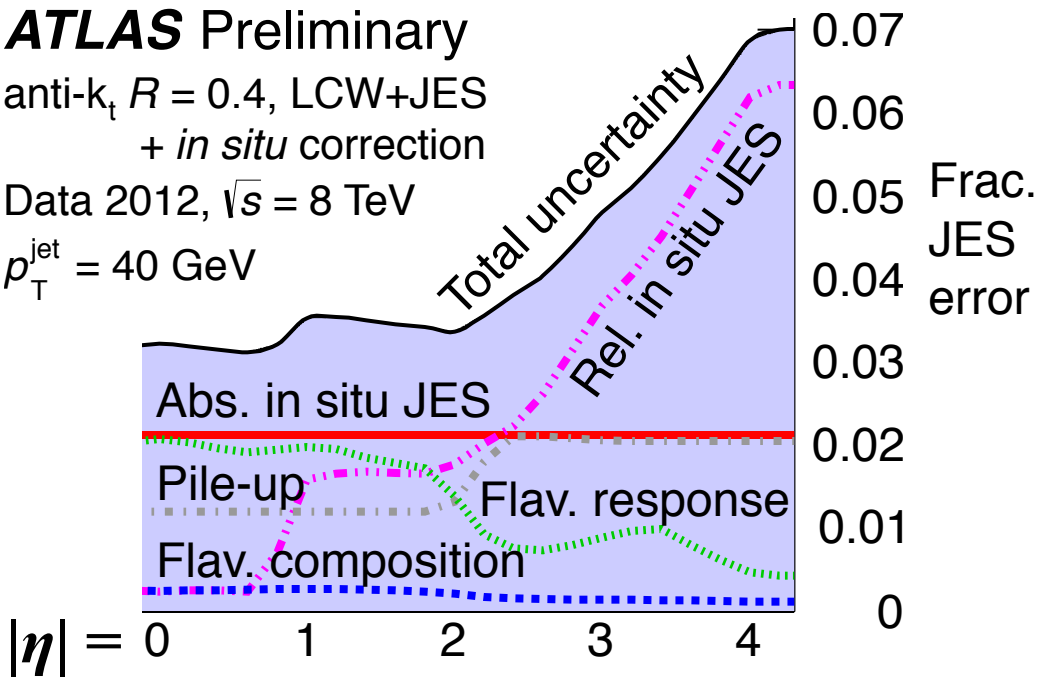
- $P_T > 25$ in tracking vol.

  Jet-vertex association to suppress pile-up (p103-104)

  $f_{JVF} > 0.5$ for $P_T < 50$ GeV

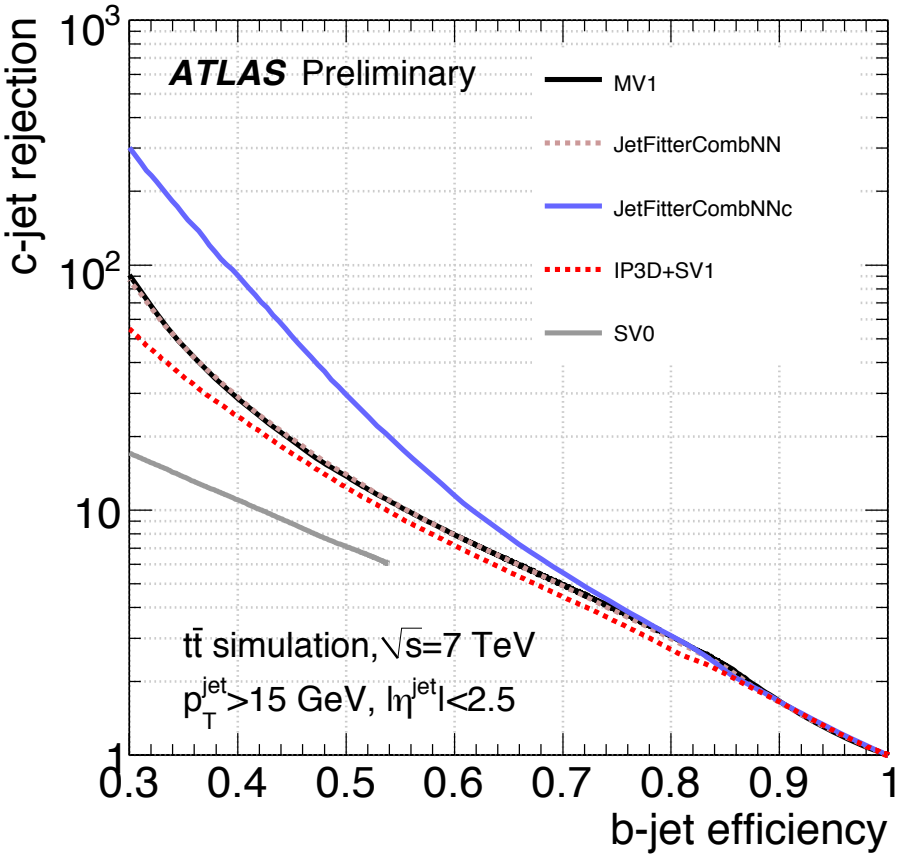
- $P_T > 30$ if forward

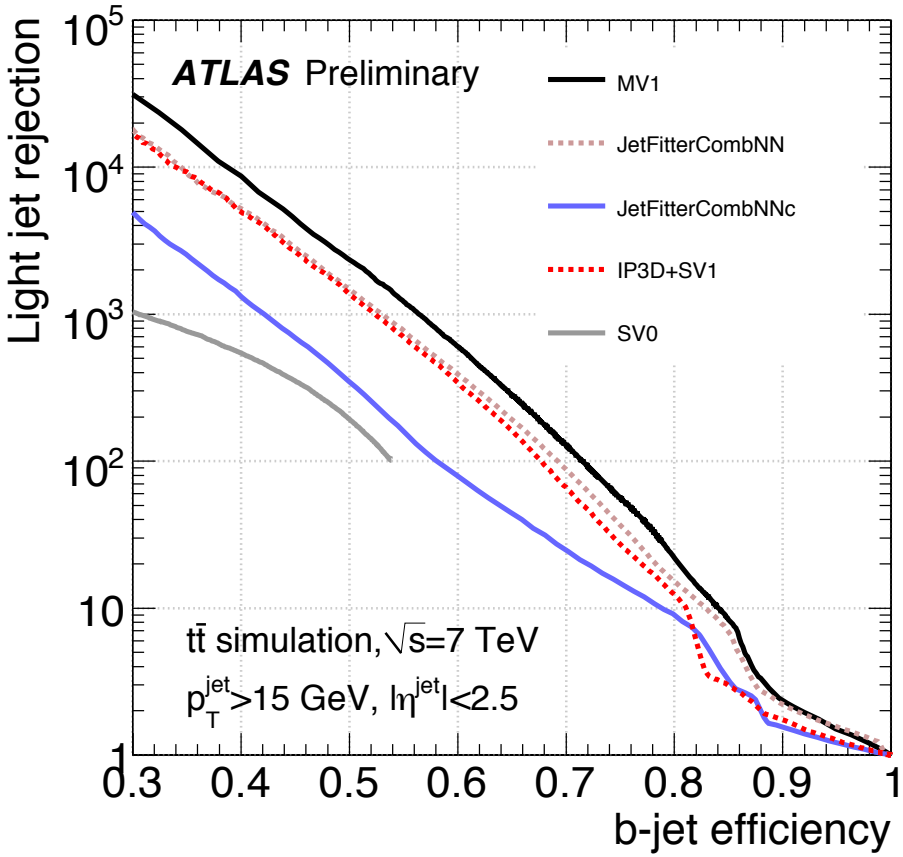
  $2.4 < |\eta| < 4.5$



b-tagging R.O.C. curves

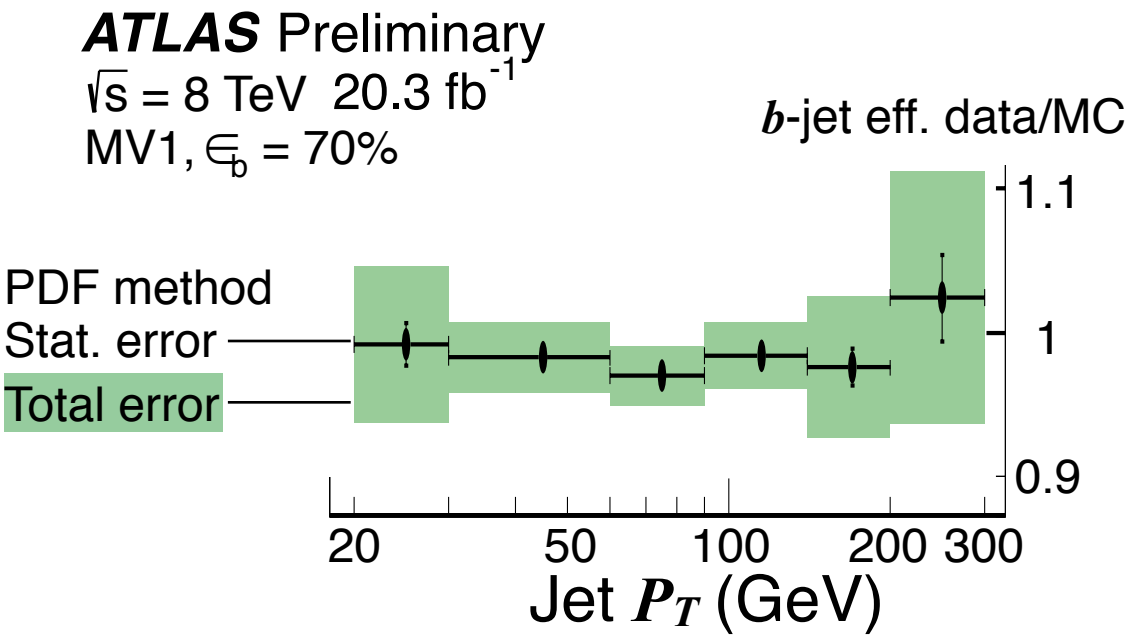
Hong





b-tagging scale factor

Hong

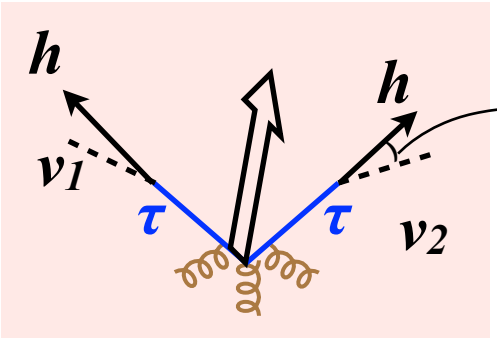


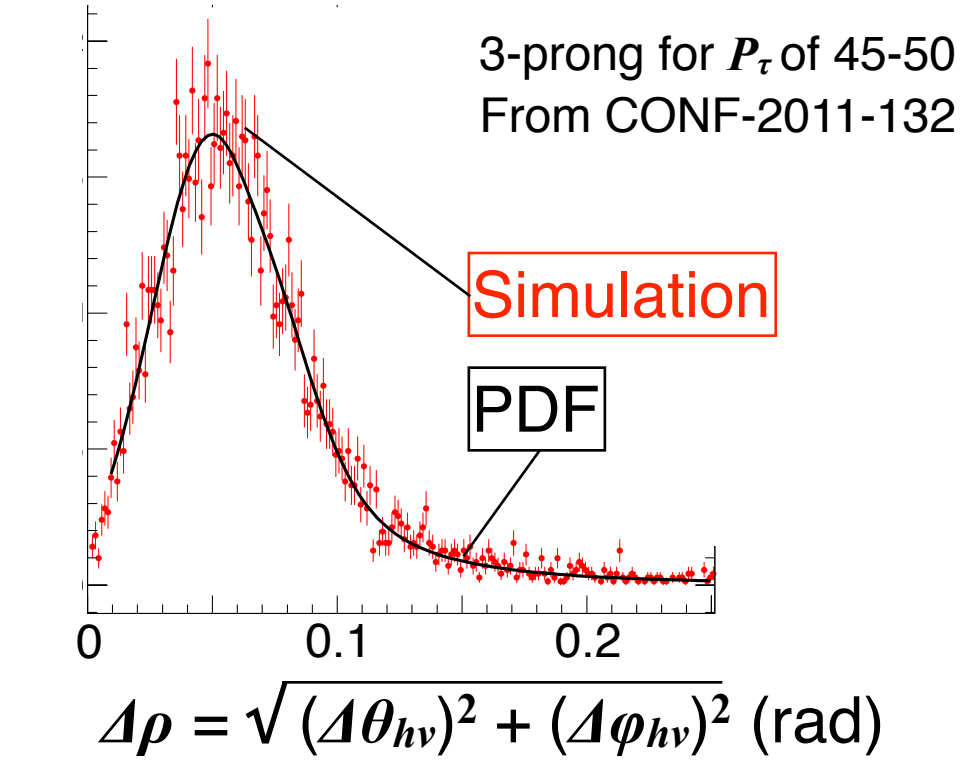
$H \to \tau\tau$ v. $Z \to \tau\tau$ separation with $M(\tau\tau)$

Hong

Statement of the problem

- MET measured, not neutrinos





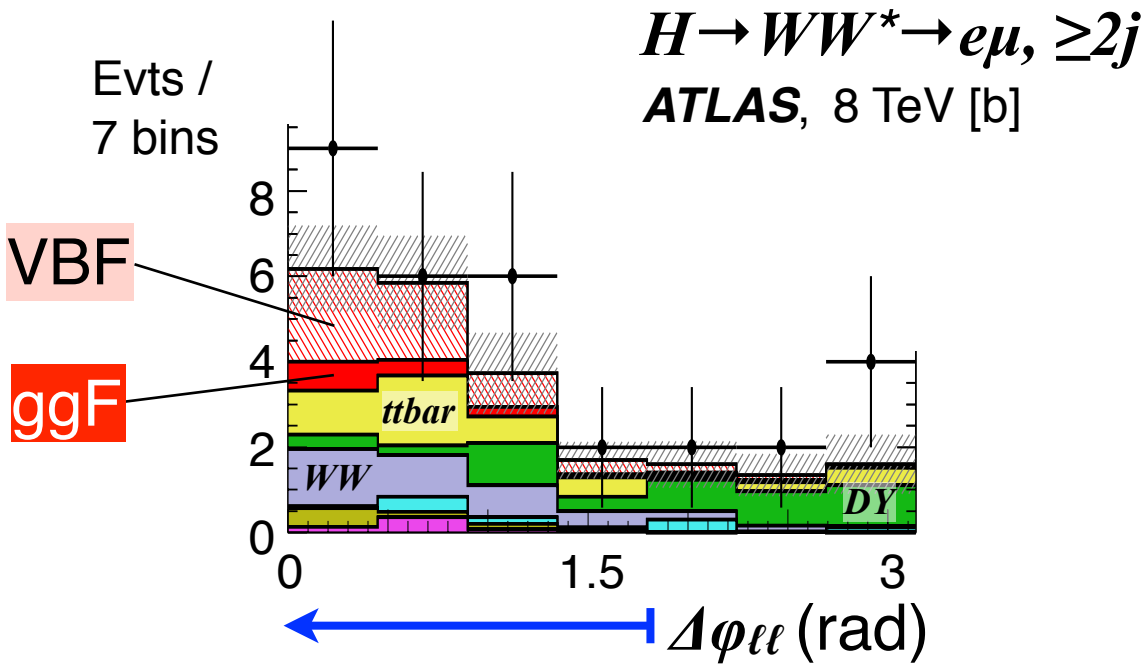
To illustrate, consider $\tau\tau \to hh\nu_1\nu_2$

- 6 components for ν_1, ν_2
- 4 eqns. $M(\nu_1 h) = 1.78$ GeV
  $M(\nu_2 h) = 1.78$ GeV
  $(P_{\nu 1}+P_{\nu 2})_x = MET_x$
  $(P_{\nu 2}+P_{\nu 2})_y = MET_y$
- 2 left. Can parametrize by set($\Delta\rho_1$, $\Delta\rho_2$)

Hint: Generate $\Delta\rho$ distributions with MC

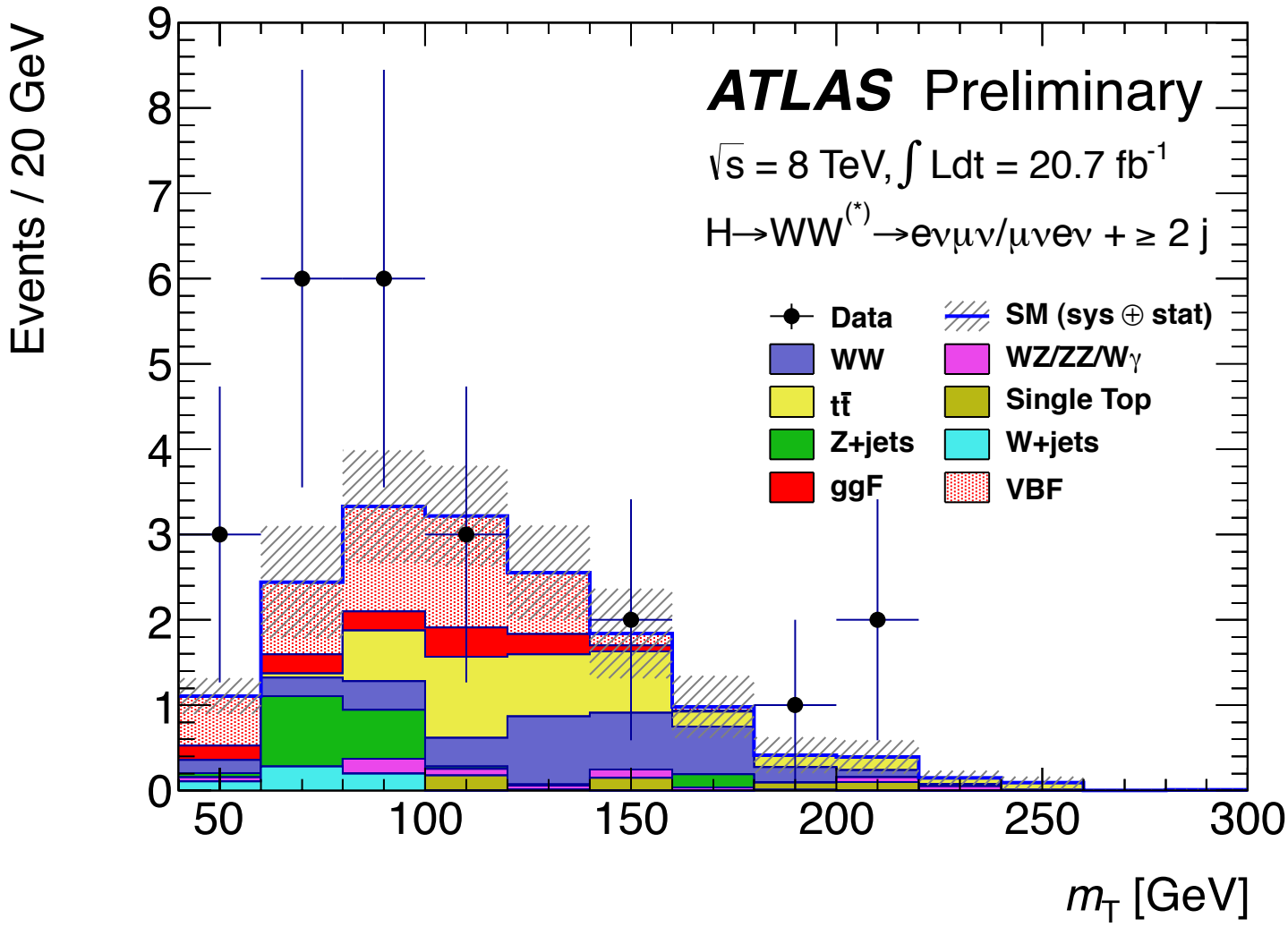
Same as p24, but for ≥ 2j

Hong



Same as p25 with legends

Hong



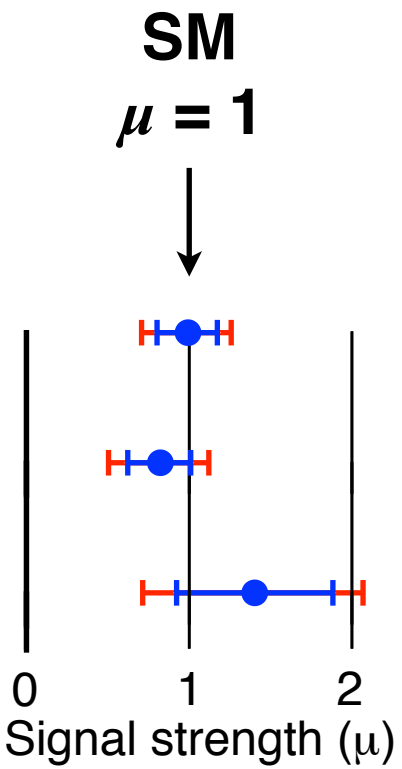
Breakdown $H \rightarrow WW^*$

Hong

$$\mu_{\text{Higgs}} = \frac{(\sigma \cdot B)_{\text{Data}}}{(\sigma \cdot B)_{\text{SM}}}$$

		stat.	experimental	theory
Total	0.99	± 0.21	± 0.17	± 0.12
$N_{Jet} \leq 1$	0.82	± 0.22	± 0.25	
$N_{Jet} \geq 2$	1.4	± 0.5	± 0.4	

Caveat emptor: The table is using 7 & 8 TeV data at M_H = 125.5 GeV combining all the production modes.



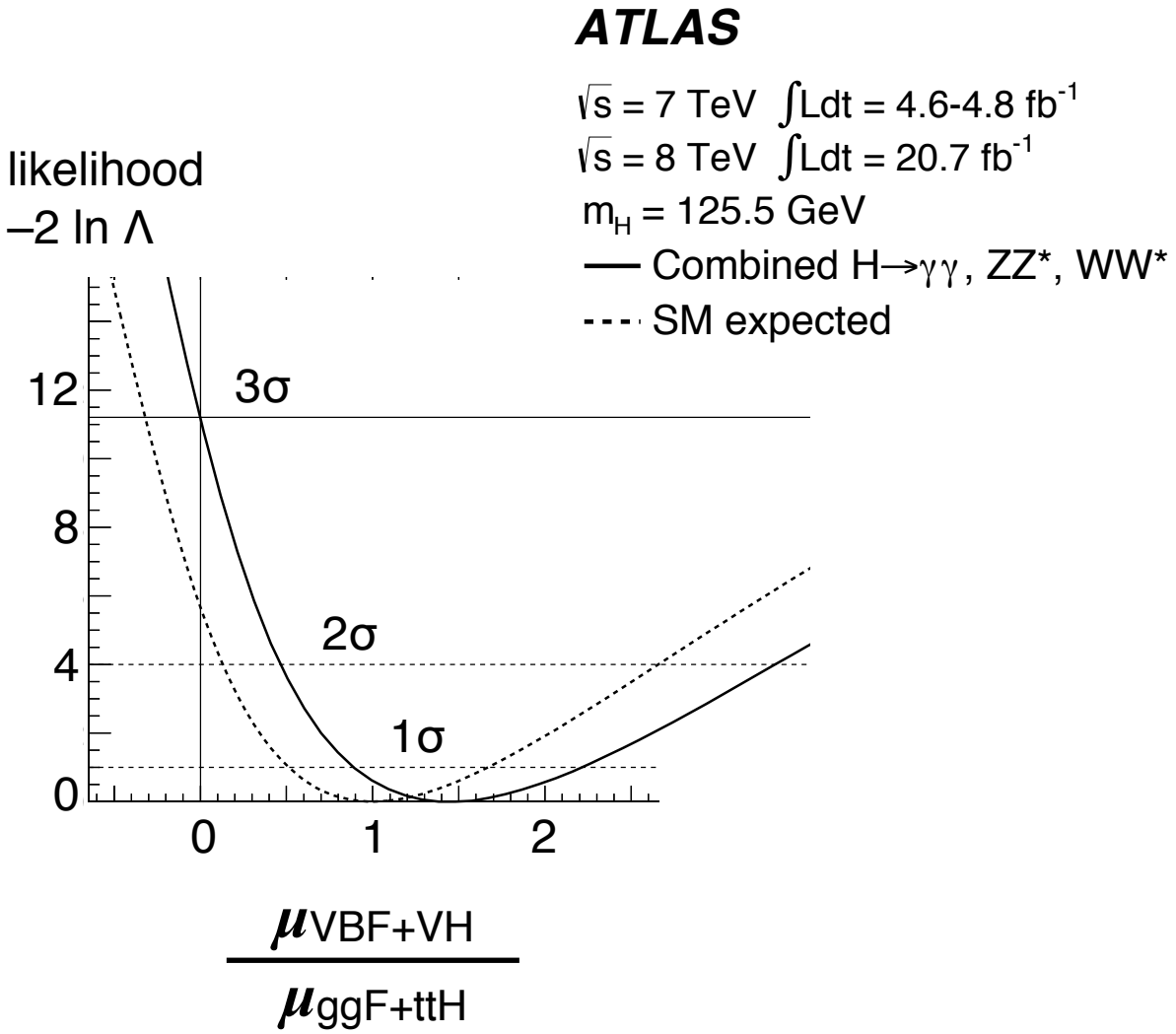
Signal significance for HWW is 3.8σ (3.8σ)

observed expected

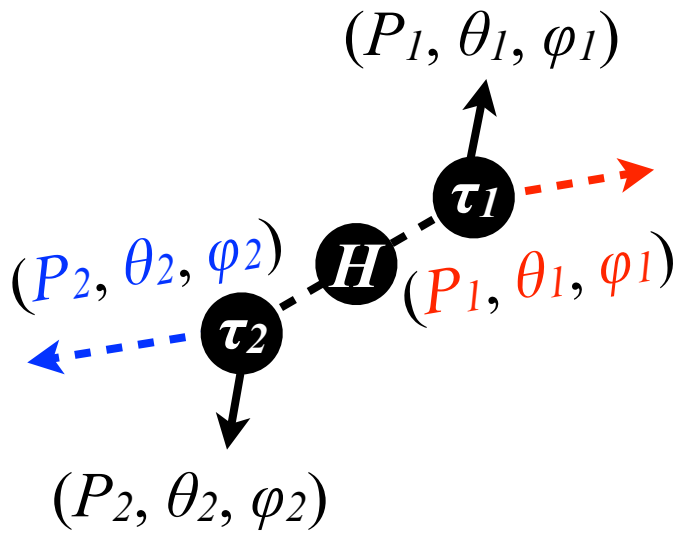
Considering only VBF HWW is 2.5σ (1.6σ)

VBF significance w.r.t. ggF

Hong

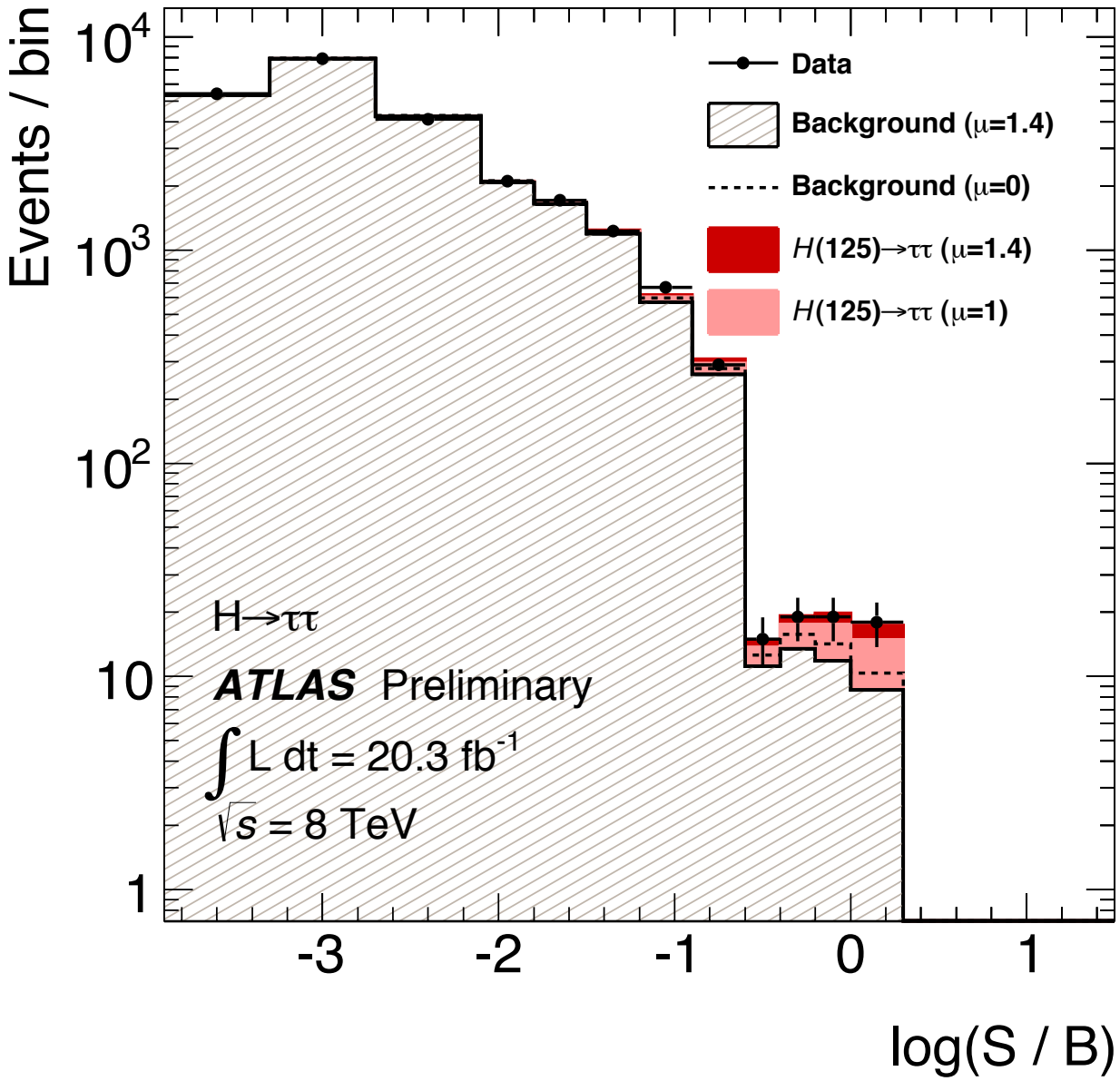


$H \rightarrow \tau\tau$ math

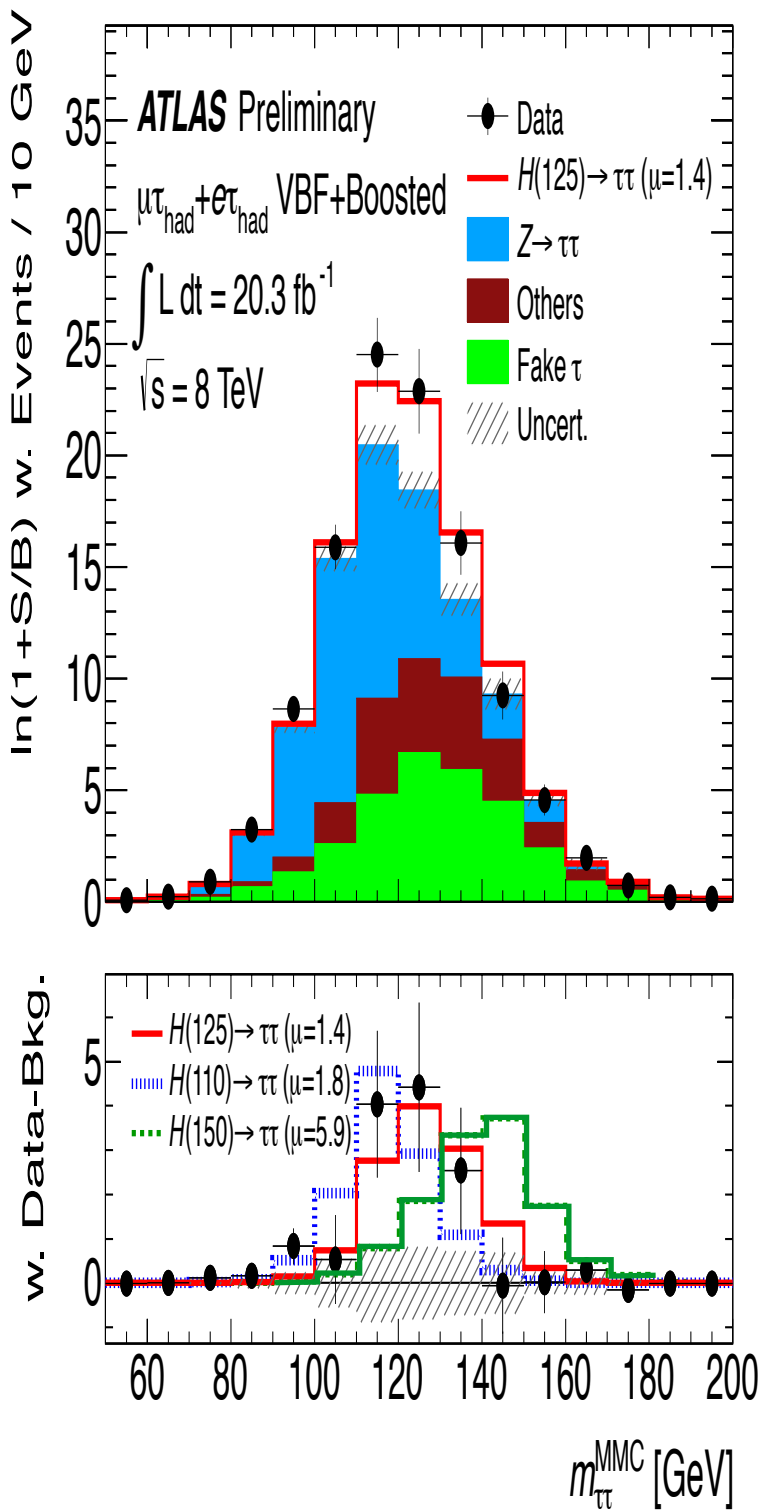


$$\mathrm{MET}_X = (P \sin\theta_1) \cdot \cos\phi_1 + (P \sin\theta_2) \cdot \cos\phi_2$$
$$\mathrm{MET}_Y = (P \sin\theta_1) \cdot \sin\phi_1 + (P \sin\theta_2) \cdot \sin\phi_2$$
$$M(\tau_1)^2 = 2 \cdot P \cdot P \cdot \big(1 - \cos(\theta_1 - \theta_1)\big)$$
$$M(\tau_2)^2 = 2 \cdot P \cdot P \cdot \big(1 - \cos(\theta_2 - \theta_2)\big)$$

Same as p41, but for combined channels

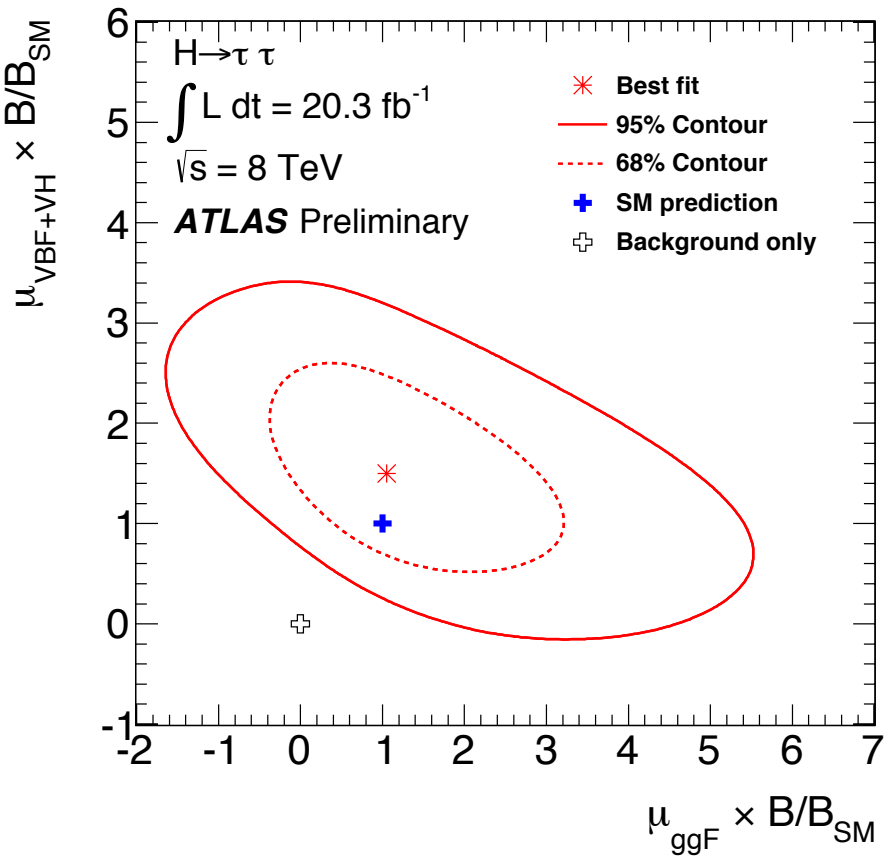


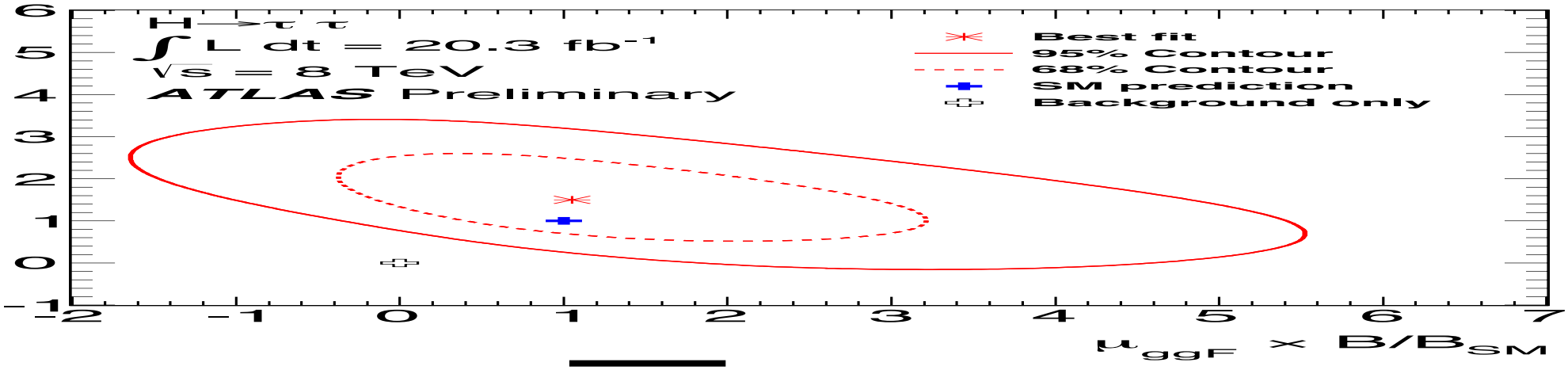
Same as p42 with legends



Same as p43, but stand-alone

Hong

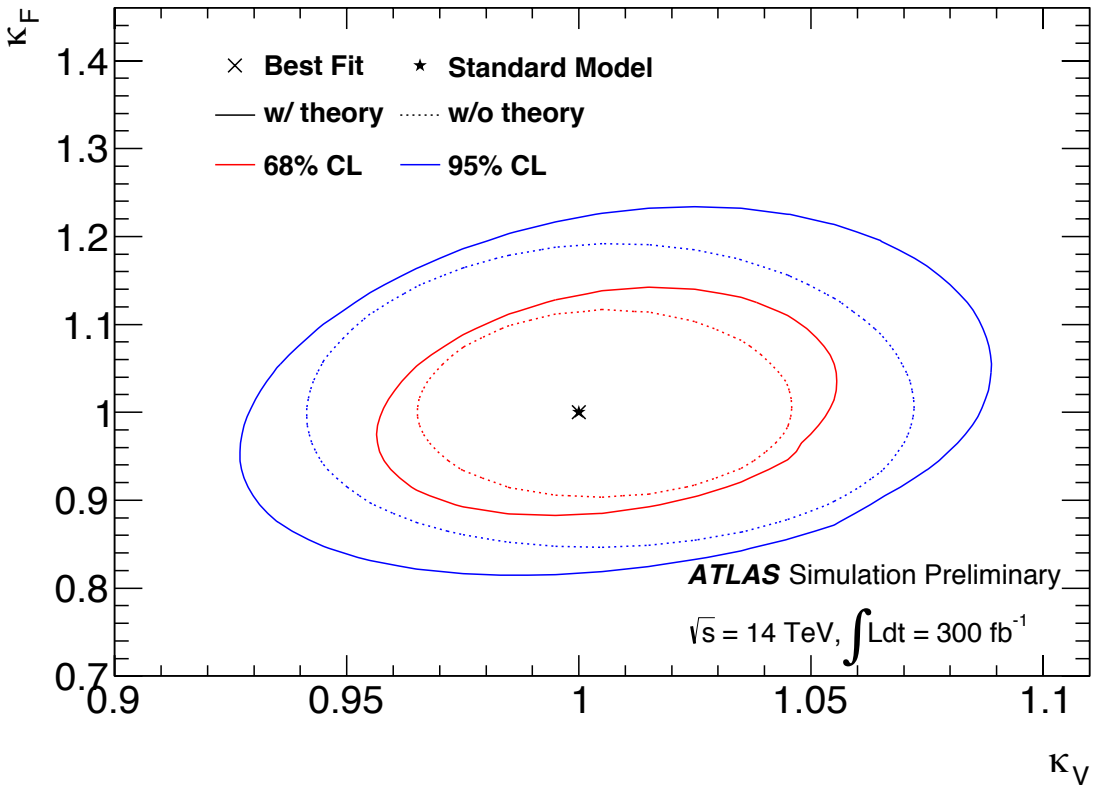


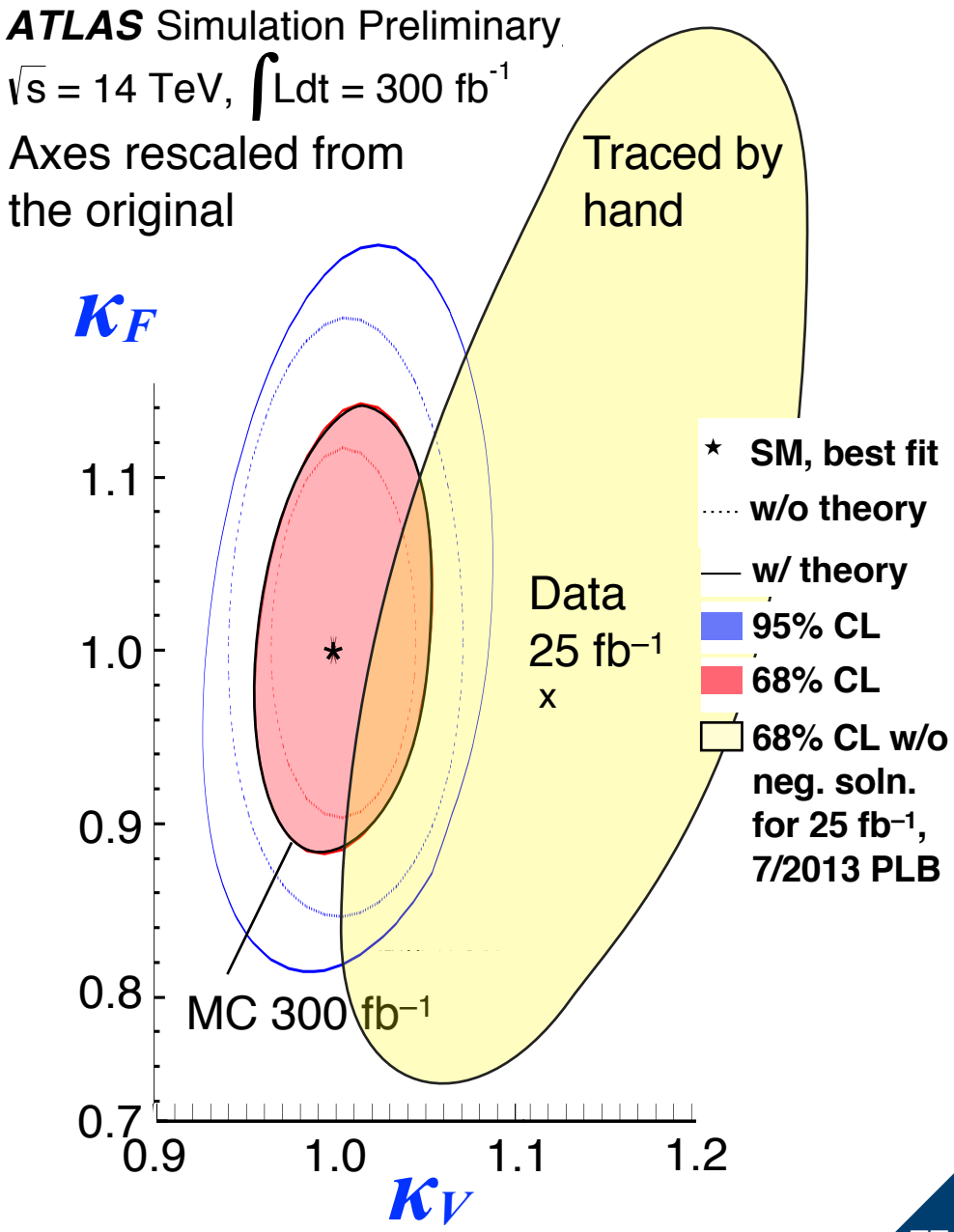


Future projections

Hong

https://cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2013–014





That’s all!